State of Wyoming
Department of
Environmental
Quality/Air Quality
Division

Exceptional Event Demonstration Package for the Environmental Protection Agency

Thunder Basin, Wyoming Ozone Standard Exceedance June 6, 2012

122 West 25TH Street, Cheyenne, WY 82002

NOTES TO READER:

This document contains several electronic enhancements such as time animations and figure enlargements. Viewing this document in its electronic format will aid the reader in reaching a better understanding of the material. In addition, this document has been prepared to stand alone as a hard copy without the electronic enhancements.

All time references refer to Mountain Standard Time (MST) unless otherwise noted. EPA utilizes Mountain Standard Time (MST) consistently throughout the entire year in respect to ambient and ground based meteorological monitoring data collection and reporting.

LIST OF ACRONYMS AND TERMS

AGL	Above Ground Level
AJAX	Alpha Jet Atmospheric eXperiment
AMSL	Above Mean Sea-level
AQS	Air Quality System
$° C\ KM^{-1}$	Degrees Celsius per Kilometer
CFR	Code of Federal Regulations
CO	Carbon Monoxide
DALR	Dry Adiabatic Lapse Rate
DU	Dobson Unit
ECC	Electrochemical Concentration Cell
EDAS	Eta Data Assimilation System
EPA	Environmental Protection Agency
ELR	Environmental Lapse Rate
GMD	Global Monitoring Division
GOES	Geostationary Operational Environmental Satellite
h7-h5	700-500 mb layer
HYSPLIT	HYbrid Single-Particle Lagrangian Integrated Trajectory
IOP	Intensive Operational Period
IPV	Isentropic Potential Vorticity
K	Kelvin
kPA	Kilopascal
LIDAR	Light Detection And Ranging
mb	Millibar
MDT	Mountain Daylight Time
MSL	Mean Sea Level
MST	Mountain Standard Time
NAAQS	National Ambient Air Quality Standards
NAM	North American Mesoscale
NARR	North America Regional Reanalysis
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NWS	National Weather Service
O_3	Ozone
ppb	Parts Per Billion
Pphm/vol	Parts Per Hundred Million / Volume
PT	Potential Temperature
PVU	Potential Vorticity Unit
QA/QC	Quality Assurance/Quality Control
RAOB	Radiosonde observations
RAP	Rapid Refresh model
RAQMS	Realtime Air Quality Modeling System
RUC	Rapid Update Cycle model

RH	Relative Humidity
SI	Stratospheric Intrusion
SO_2	Sulfur Dioxide
SPC	Storm Prediction Center
START08	Stratosphere-Troposphere Analyses of Regional Transport 2008
UG	Upper Green
UGRB	Upper Green River Basin
UGWOS	Upper Green Winter Ozone Study
UTC	Coordinated Universal Time
UV	Ultraviolet
WDEQ/AQD	Wyoming Department of Environmental Quality/Air Quality Division
VOC	Volatile Organic Compound

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EXECUTIVE SUMMARY

The Wyoming Department of Environmental Quality/Air Quality Division (WDEQ/AQD) has determined that a stratospheric intrusion created elevated ozone readings resulting in an 8-hour ozone standard exceedance at the Thunder Basin, Wyoming ozone monitor located in northeastern Wyoming on June 6, 2012 (refer to Figure 1 for location of Thunder Basin).

During the interval from late winter to late spring in the northern hemisphere, weather producing systems (i.e. tropospheric storm systems, upper level disturbances or upper level storm systems) aid in causing the tropopause to "fold" or descend into the troposphere where our weather occurs. Tropopause folding permits ozone-rich air from the stratosphere to enter the troposphere, also called a stratospheric intrusion (SI), creating the potential for ground level ozone monitors over the higher terrain of the western United States to experience elevated readings.

On June 6, 2012, an upper air level disturbance produced an SI affecting the Thunder Basin, Wyoming monitor resulting in a maximum daily 8-hour average ozone level of 88 parts per billion (ppb). Aiding in the elevated 8-hour levels were 1-hour average ozone values that were in the mid-to-upper 90's ppb. Additionally, several other AQD monitors throughout Wyoming recorded elevated hourly concentrations, however none of the other monitors exceeded the 8-hour ozone standard. Figure 2 portrays 1-hour average ozone data for June 5-7, 2012 at the Thunder Basin, Campbell County, Gillette, South Pass, Boulder, Daniel, Pinedale, and Big Piney, Wyoming monitors. Because of the SI, elevated ozone occurred at South Pass (91 ppb, 1-hour average) at 12 am MST, June 6, 2012 and continued at the other Wyoming sites during June 6, 2012.

It has been documented (T. S. ENVIRON 2008) that elevated ozone values can occur at the UGRB ozone monitors of Boulder, Big Piney, Pinedale, and Daniel because of light winds, snow cover, and strong inversions during the January-March winter ozone season. However, during the June 6, 2012 period of elevated ozone, strong winds buffeted the UGRB prior to the SI event, and no snow cover or strong inversions were present. Accumulation of surface-based ozone precursors did not occur because meteorological conditions were not supportive of precursor buildup prior to elevated ozone readings.

Statistical analyses performed on the Thunder Basin data show that the June 6, 2012 ozone data was statistically significantly higher than values recorded during June of each year starting in 2001 and ending in 2012. The AQD performed a careful evaluation of the June 6, 2012 episode, and is confident that the Thunder Basin event presented in this document is the result of a stratospheric intrusion.

Quality Assurance/Quality Control (QA/QC) checks of the Thunder Basin ozone monitor during 2012 confirm that the monitor was running properly. Independent audit results for the second and fourth quarters of 2012 are consistent with 40 CFR Part 58, Appendix A, Section 3.2 and the *Quality Assurance Project Plan* for the Thunder Basin monitoring project.

With the preceding points in mind, the WDEQ/AQD submits the June 6, 2012 Thunder Basin ozone exceedance as a case for the Environmental Protection Agency's (EPA) concurrence regarding the stratospheric intrusion of ozone as being an exceptional event as outlined by the final "Treatment of Data Influenced by Exceptional Events" Final Rule. The WDEQ/AQD presents supporting evidence, which clearly shows that the exceptional event passed the four required tests A-D under 40 CFR 50.14 (3)(iii). Specifically:

> **(A)** The event satisfies the criteria set forth in 40 CFR 50.1(j);
> **(B)** There is a clear causal relationship between the measurement under consideration and the event that is claimed to have affected the air quality in the area;
> **(C)** The event is associated with a measured concentration in excess of normal historical fluctuations, including background; and
> **(D)** There would have been no exceedance or violation but for the event.

Figure 1. WDEQ/AQD air quality monitor network sites during 2012.

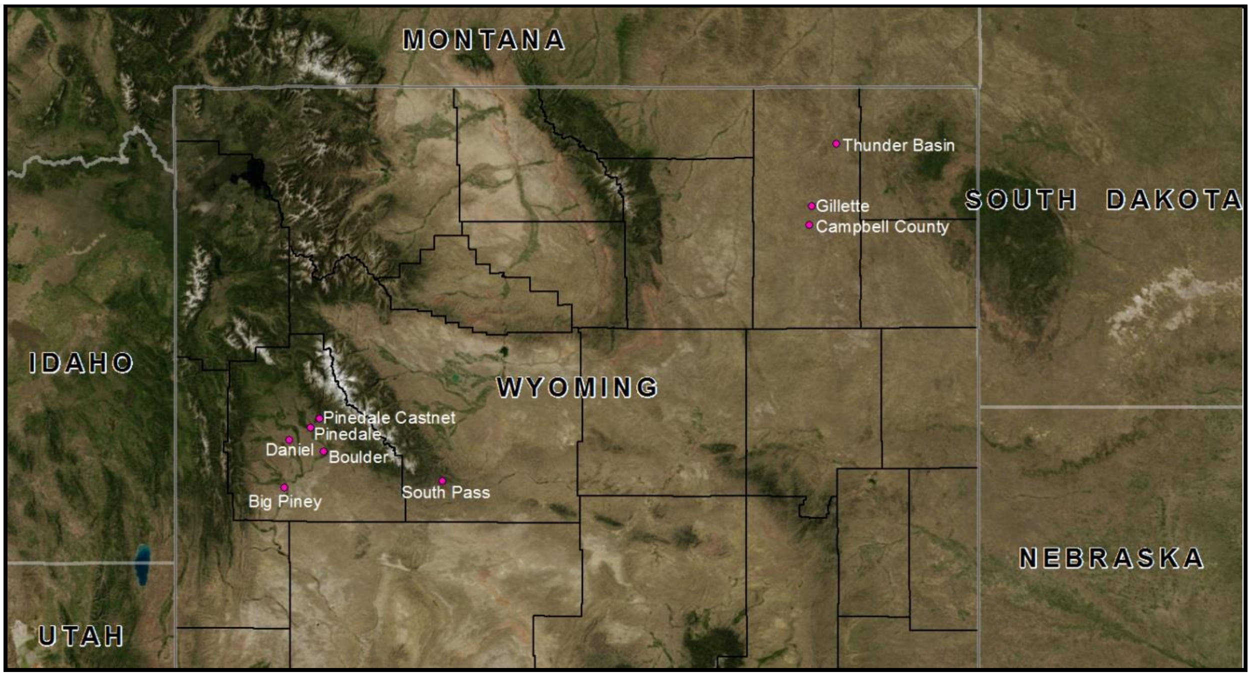
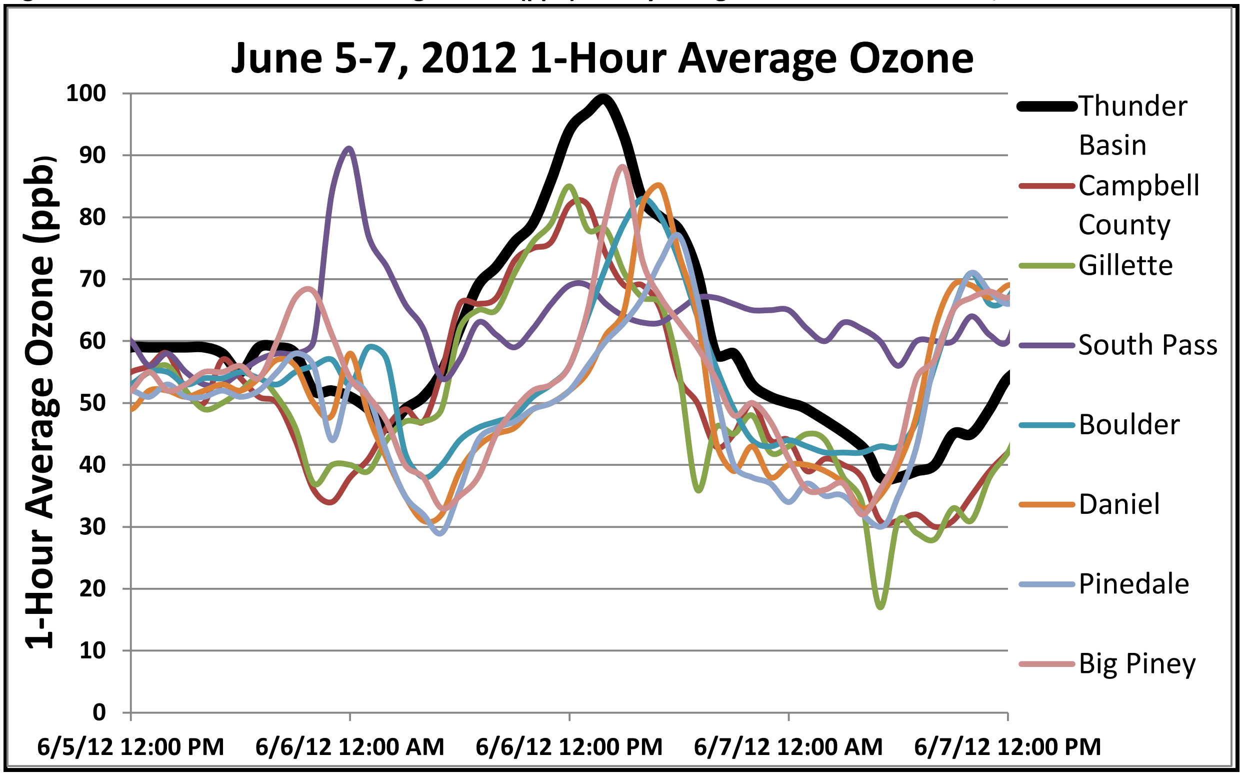


Figure 2. Time series of 1-hour average ozone (ppb) for Wyoming monitors from June 5-7, 2012.



Criteria **(A)** states that "[t]he event satisfies the criteria set forth in 40 CFR 50.1(j)":

40 CFR 50.1 (j) requires that an exceptional event "affects air quality, is not reasonably controllable or preventable..." and is a "...natural event[s]". The Exceptional Events Rule Preamble and the 40 CFR 50 Appendices I & P specifically list stratospheric intrusion of ozone as a natural event that could affect ground level ozone concentrations. This packet includes data and graphics that display a weather disturbance, and clearly show an intrusion of stratospheric air that affected ambient air quality during June 6, 2012 at the Thunder Basin monitor.

Criteria **(B)** states that **"**[t]here is a clear causal relationship between the measurement under consideration and the event that is claimed to have affected the air quality in the area":

The causal relationship is a basic one in which the ozone standard exceedance was caused by tropospheric folding resulting in an SI. For the exceedance that occurred on June 6, 2012 an intrusion of stratospheric air occurred over or just upwind of the Thunder Basin monitor and injected ozone-rich air into the area above and surrounding the Thunder Basin monitor. The causal nature of the SI's impact on ozone values at the Thunder Basin monitor is further supported by the corroboration of ground-based air quality data to the spatial and temporal accuracy of the meteorological analysis.

Criteria **(C)** states that **"**[t]he event is associated with a measured concentration in excess of normal historical fluctuations, including background":

Statistical analysis of June 6, 2012 data clearly shows that the exceptional event was statistically significantly higher than data recorded during prior months of June from 2001 to 2012 at the Thunder Basin monitor.

Criteria **(D)** states that "[t]here would have been no exceedance or violation but for the event":

The SI allowed ozone-rich air to descend to the Thunder Basin monitor area and created elevated 1-hour average ozone values. The exceedances of the ozone National Ambient Air Quality Standards (NAAQS) would not have occurred "but for" the SI.

The 75th percentile hourly concentrations do not exceed 60 ppb on any of the years tested (2001-2012) for statistical significance. Hourly concentrations monitored during June 6, 2012 were outliers for the month of June 2001-2012. Statistics demonstrating that ozone levels were unusually elevated affirm that the exceedance of the ozone National Ambient Air Quality Standards (NAAQS) would not have happened "but for" the SI event having occurred during June 6, 2012.

In summary, the WDEQ/AQD concludes that an SI event occurred during June 6, 2012 resulting in an exceptional event. This exceptional event has passed the four criterion tests under 40 CFR 50.14 (3)(iii). Consequently, the WDEQ/AQD is requesting EPA's concurrence that the event was exceptional and for the exclusion from the Air Quality System (AQS) database of the Thunder Basin 1-hour average ozone data for the following times:

Table 1. Thunder Basin Times and Dates for AQS data exclusion.

Begin Time/Date(s)	End Time/Date(s)
0600 MST June 6, 2012	1900 MST June 6, 2012

BACKGROUND

Document Format

The following discussion provides background information on SI's as well the methodology utilized in identifying SI's. Subsequently, the June 6, 2012 event is presented with evidence supporting the premise that an SI occurred creating a period of elevated 1-hour average ozone values resulting in an ozone standard exceedance at the Thunder Basin ozone monitor. The reader is encouraged to examine Appendix A, "Documented Stratospheric Intrusion Events" and Appendix B, "Diagnosis Example" to obtain further information on SI's.

Ground Level Ozone Formation

"Ozone (O_3) is a gas composed of three oxygen atoms. It is not usually emitted directly into the air, but at ground level is created by a chemical reaction between oxides of nitrogen (NOx) [including nitrogen dioxide (NO_2)] and volatile organic compounds (VOCs) in the presence of sunlight. Ozone has the same chemical structure whether it occurs miles above the earth or at ground level and can be "good" or "bad," depending on its location in the atmosphere." (Source: EPA website). Specifically, NO_2 is split up by ultraviolet (UV) sunlight to give nitric oxide (NO) and an oxygen atom, which combines with molecular oxygen (O_2) to give ozone. Calm winds, or stagnant conditions assist the process of allowing the O_3 precursors of NO_x (NO_2) and VOCs to accumulate in order to produce O_3. Unlike ozone of stratospheric origin, ground-based ozone typically forms during the daylight hours under stagnant weather conditions (over several days in some cases) and dissipates a few hours after sunset.

Atmospheric Structure

The troposphere is the layer of air adjacent to the earth's surface and contains our weather (i.e. wind, rain, snow, thunderstorms, etc.) The troposphere also contains variable amounts of water vapor and carbon monoxide (CO), extends to a height of roughly 11 km (6.8 mi) AMSL, and varies in depth from the earth's polar regions to the equator. Directly above the troposphere, the stratosphere exists with the tropopause separating the stratosphere from the troposphere. The tropopause is "...usually characterized by an abrupt change of lapse rate[1]" (American Meteorological Society 2010).

The stratosphere is the "...region of the atmosphere extending from the top of the troposphere [the tropopause], at heights of roughly 10–17 km...[and] is characterized by constant or increasing temperatures with increasing height and marked vertical stability" (American Meteorological Society 2010).

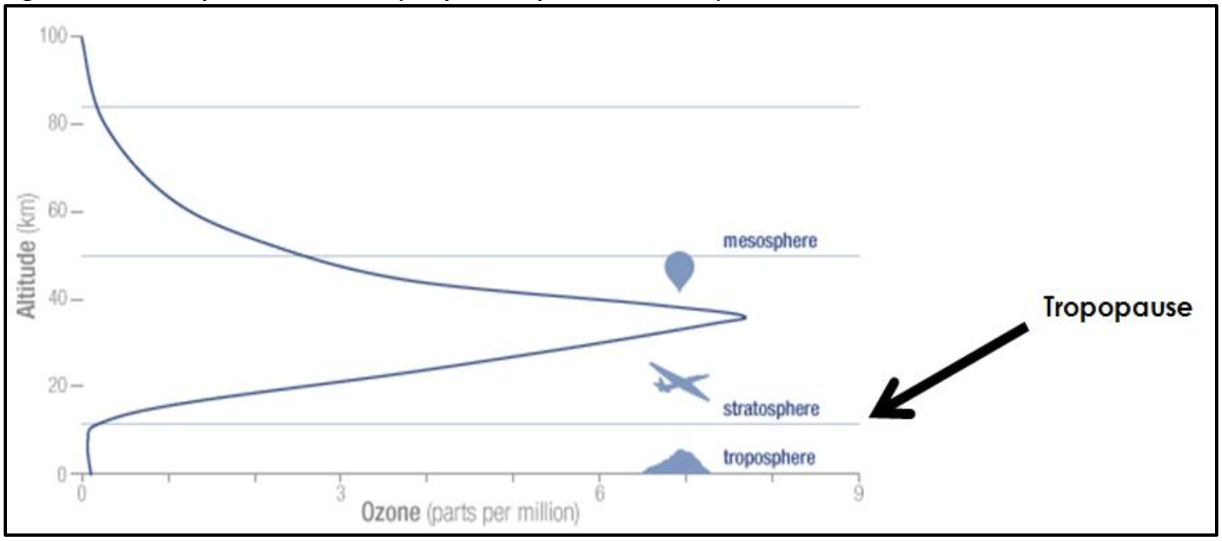
Composition of Stratospheric Air

"While the major constituents of the stratosphere are molecular nitrogen and oxygen, just as in the troposphere, the stratosphere contains a number of minor chemical species that result from photochemical reactions in the intense ultraviolet radiation environment. Chief among these is ozone..." (American Meteorological Society 2010). While the troposphere contains variable amounts of O_3, CO, and water vapor, the stratosphere lacks CO and water vapor (Pan, Randel, et

[1] Lapse rate is defined as the change of temperature with the increase of height in the atmosphere.

al. 2004; Newell, et al. 1999; Stoller, et al. 1999). Figure 3 demonstrates the typical concentration of ozone with height extending from the earth's surface through the stratosphere.

Figure 1. Vertical profile of ozone. (Graphic adapted from NASA).



Stratospheric Intrusions, Tropospheric Folding, and Identifying Stratospheric Air

Weather producing systems (i.e. tropospheric storm systems, upper level disturbances or upper level storm systems) contain atmospheric spin or vorticity, which induces vertical motion: either upward or downward motion. From late winter to late spring in the northern hemisphere, vertical motion associated with upper level disturbances aids in causing the tropopause to "fold" or descend into the troposphere where our weather occurs (Danielsen 1968). Because of tropopause folding, an intrusion of stratospheric air containing high concentrations of ozone penetrates into the troposphere (Reed 1955) releasing ozone-rich air from the stratosphere to the troposphere. As a result, the SI creates the potential for ground level ozone monitors over the higher terrain of the western United States to experience elevated ozone readings.

SI's are a tangible phenomenon. One study (Click to view press release regarding study) analyzed over 105,000 aircraft soundings, and discovered that just over 50% of the soundings contained regions of high ozone and low water vapor content occurring below the tropopause (Newell, et al. 1999). The presence of areas of high ozone concentrations and low water vapor located below the tropopause are components of an SI signature.

While the concentrations of O_3, CO, and relative humidity (RH) aid one in identifying air of stratospheric origin, additional stratospheric tracers[2] should be employed and include: isentropic potential vorticity (IPV) and potential temperature (PT). IPV is a proxy for atmospheric spin and is a conservative property[3] with values of up to two orders of magnitude [100 times] greater for stratospheric air than that of tropospheric air (Shapiro 1980). Therefore, IPV can serve as a

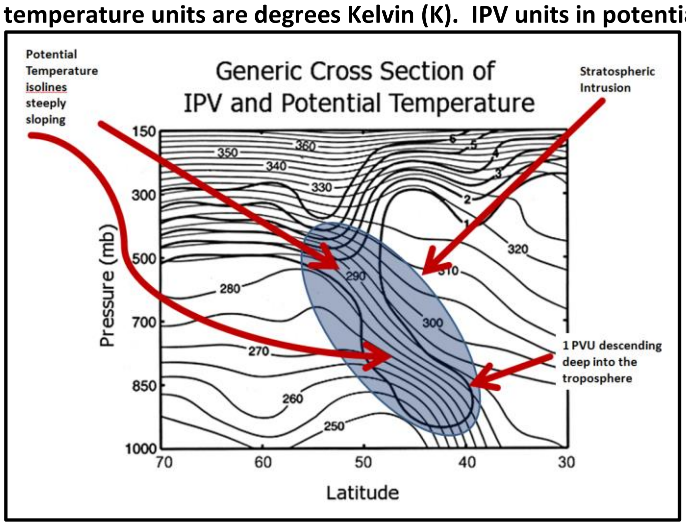
[2] "A chemical or thermodynamic property of the flow that is conserved during" air motion (American Meteorological Society 2010).

[3] "A property with values that do not change in the course of a particular series of events" (American Meteorological Society 2010). Namely, a property whose values do not change over the course of travel.

tracer of stratospheric air. One unit of IPV (1-PVU)[4] typically represents the tropopause (Shapiro 1980), and as one ascends beyond the tropopause into the stratosphere, the value of IPV increases correspondingly. However, within the last decade a study by Pan revealed that using only IPV to define the tropopause is problematic. In fact, the thermal tropopause height "...spans a broad range of..." IPV values and varies latitudinally and seasonally (Pan 2004). Therefore, based on the AQD's review of the background material regarding IPV usage, the AQD recognizes that one cannot use IPV alone in identifying air of stratospheric origin.

Potential temperature is "the temperature that an unsaturated parcel of dry air would have if brought adiabatically[5] and reversibly from its initial state to a standard pressure, p0, typically 100 kPa" (or 1000 mb) (American Meteorological Society 2010). Stratospheric air has much higher values of potential temperature than that of tropospheric air. As stratospheric air penetrates the troposphere, its potential temperature is higher than that of tropospheric air surrounding the SI. One can visualize this effect by cross-section examination of IPV and PT. The slope of isolines[6] of potential temperature increase markedly showing this effect (Reed 1955). Figure 4 shows a generic vertical cross-section of IPV and PT. Note the area of sloping isolines of PT and the 1-PVU surface juxtaposed on one another. The slope of the isolines of PT increases significantly highlighting the signature of stratospheric air descending into the troposphere.

Figure 2. Vertical cross-section of potential temperature (thin solid lines) and IPV (thick solid lines). Potential temperature units are degrees Kelvin (K). IPV units in potential vorticity units. Click image to enlarge.



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[4] IPV and PVU are utilized throughout this document and are synonymous. For further information, please consult: http://www.comet.ucar.edu/class/aes_canada/04-1/html/docs/PVintro.pdf

[5] "Adiabatic process—A process in which a system does not interact with its surroundings by virtue of a temperature difference between them. In an adiabatic process, any change in internal energy (for a system of fixed mass) is solely a consequence of working. For an ideal gas and for most atmospheric systems, compression results in warming, expansion results in cooling" (American Meteorological Society 2010). Compression and expansion arise from downward atmospheric vertical motion and atmospheric upward vertical motion respectively.

[6] "... a line of equal or constant value of a given quantity, with respect to either space or time…" (American Meteorological Society 2010)

Background Summary

The stratosphere contains high concentrations of ozone compared to the troposphere. At times, from late winter until late spring in the northern hemisphere, tropospheric storm systems act synergistically with tropopause folds to inject stratospheric ozone into the troposphere via an SI. Compared to tropospheric air, stratospheric air is typically much drier, has higher values of IPV and PT, and contains lower quantities of CO.

Data from research aircraft have determined that tropopause folds (SI's) contain ample O_3, dry air, and low concentrations of CO. Mathematical calculations based on the aircraft data also verify that the SI's had greater than 1-PVU and had higher PT values compared to those of the troposphere surrounding the SI.[7]

[7] The reader is encouraged to examine Appendix A, "Documented Stratospheric Intrusion Events" and Appendix B, "Diagnosis Example" to obtain further information on SI's.

METHODOLOGY FOR DIAGNOSING SI'S AND SI EVENTS

Since the majority of SI's occur from the late winter to late spring (Danielsen 1968), elevated ozone episodes occurring during this time merit further analysis. The AQD recognizes that a combination of indicators should be employed when diagnosing an SI. One should not rely on any single indicator alone. The following offers a methodology to diagnose whether an SI has occurred:

- Summary of the synoptic scale meteorology

  An examination of the 500 mb heights and vorticity chart may indicate an SI if an upper level atmospheric disturbance occurred at some point before ground level ozone values increased. By inspecting the 500 mb pressure chart by way of the North America Regional Reanalysis (NARR)[8], one can establish whether an upper atmospheric disturbance took place.

- Employ Geostationary Operational Environmental Satellite (GOES) data

  "GOES satellites provide the kind of continuous monitoring necessary for intensive data analysis. They circle the Earth in a geosynchronous orbit, which means they orbit the equatorial plane of the Earth at a speed matching the Earth's rotation. This allows them to hover continuously over one position above the Earth's surface. The geosynchronous plane is about 35,800 km (22,300 miles) above the Earth, high enough to allow the satellites a full-disc view of the Earth....the main mission [of GOES satellites] is carried out by the primary instruments, the imager and the sounder. The imager is a multichannel instrument that senses radiant energy and reflected solar energy from the Earth's surface and atmosphere. The Sounder provides data to determine the vertical temperature and moisture profile of the atmosphere, surface and cloud top temperatures, and ozone distribution." (Source: NOAA Satellite and Information Service, National Environmental Satellite, Data, and Information Service, Office of Satellite Operations website).

  Recent studies and research have shown that usage of GOES data is a useful tool in diagnosing SI's (Jin, et al. 2008). One can use the GOES total column ozone [9]data in

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[8] "The North America Regional Reanalysis (NARR) Project is a reanalysis of historical observations using a 32-km version of the National Centers for Environmental Prediction (NCEP) 1993 operational ETA model and ETA data assimilation system (EDAS)....The domain of analyses includes North and Central America...The period of the reanalyses is from October 1978 to the present and analyses were made 8 times daily (3 hour intervals). Horizontal boundary conditions are derived from the NCEP/DOE Global Reanalysis." For further information, please refer to visit this website: http://www.esrl.noaa.gov/psd/data/gridded/data.narr.html

[9] Total column ozone (TCO) is estimated every hour using GOES Sounder data. The ozone retrieval is generated by application of a regression technique as described in Li et al 2007. Estimates are currently limited to cloud-free regions of the GOES-E (12) & -W (11) Sounder sectors. Each image is a Derived Product Image (DPI), wherein an 8-bit brightness value representing TCO is assigned within the retrieval program for each cloud-free Field-of-View (FOV). Band-8 (11.0um) is used for the DPI image background. Total column ozone is measured in Dobson Units (100 DU = 1 mm of thickness at Standard Temperature and Pressure (STP)). Features such as upper level low-pressure systems and frontal boundaries can often be identified in the TCO imagery. (Source: Data Center at the Space Science and Engineering Center (SSEC) of the University of Wisconsin – Madison)

Dobson Units (DU)[10] to locate areas of increased column ozone (Wimmers, et al. 2003; Knox and Schmidt 2005). Numerous studies have shown a positive correlation between an SI and an increase in the total column ozone. As the SI injects ozone into the troposphere, total column ozone increases (Reed 1950; Schubert and Munteanu 1988; Mote, Holton and Wallace 1991).

The GOES Band-12 channel is a water vapor channel that portrays the moisture content of the layer approximating 300-400 mb (Wimmers, et al. 2003). Use of the water vapor image helps highlight an area of substantially drier air originating from aloft mixing down to lower levels of the troposphere. Since SI's contain dry air and transverse through the 300-400 mb tropospheric layer, one can use the 6.5-micrometer GOES Band-12 water vapor channel to diagnose the presence of an SI signature.

- Employ Radiosonde observations

Another way to diagnose the existence of stratospheric air is by examining Radiosonde observations (RAOB's). RAOB's are comprised of three elements: a radiosonde (an instrument that measures and transmits pressure, relative humidity, and temperature data to a ground receiver), a parachute, and a balloon. The balloon is released into the sky carrying the radiosonde and parachute. A layer of dry air is a key signature of stratospheric air (as measured by a radiosonde) and is depicted by an increase in temperature and a decrease in dew point (moisture) with height (Newell, et al. 1999; Stoller, et al. 1999).

When coupled with a radiosonde, an ozonesonde provides direct evidence of the vertical profile of ozone concentration. An ozonesonde contains an electrochemical concentration cell (ECC) that senses ozone as is reacts with a dilute solution of potassium iodide to produce a weak electrical current proportional to the ozone concentration (partial pressure) of the sampled air.

- Employ 4-D "0-hour" Rapid Refresh (RAP) data (IPV, RH, and PT)

The RAP is a numerical weather analysis tool utilized by meteorologists to predict weather conditions. The RAP is initialized with real-time data, and the 0-hour analysis for any given hour is a very close approximation to initial actual conditions (Benjamin, et al. 2004). RAP "analysis" data can be used to illustrate the signature of an SI (refer to Figure 4) by portraying IPV, RH, and PT (Murray 2003) via a vertical cross-section or a time-height cross-section of the atmosphere.

[10] The Dobson Unit is the most common unit for measuring ozone concentration. One Dobson Unit is the number of molecules of ozone that would be required to create a layer of pure ozone 0.01 millimeters thick at a temperature of 0 degrees Celsius and a pressure of 1 atmosphere (the air pressure at the surface of the Earth). Expressed another way, a column of air with an ozone concentration of 1 Dobson Unit would contain about 2.69x1016 ozone molecules for every square centimeter of area at the base of the column. Over the Earth's surface, the ozone layer's average thickness is about 300 Dobson Units or a layer that is 3 millimeters thick.

- Utilize lapse rate analysis

  Employ the use of the environmental lapse rate (via the 20-km RUC 0-hour analysis) to demonstrate that stratospheric air was able to "mix-down" from the SI to the monitor location. The environmental lapse rate (ELR) is defined as "the rate of decrease of temperature with elevation" (American Meteorological Society 2010). When the environmental lapse rate (actual temperature profile) approaches the dry adiabatic lapse rate of 9.8^{o} C km^{-1}, the atmosphere trends toward being able to mix in the vertical more readily.

  ELR can be determined by examining the 700 to 500 mb (h7-h5) layer (or a layer near the h7-h5 such as the 750 to 550 mb layer). The h7-h5 layer represents the lower to mid-levels of the troposphere and is a vertical "bridge" between ozone monitoring sites at higher elevations and the location of an SI[11].

SUMMARY OF DIAGNOSING SI EVENTS

To review, the key features of a SI event are:

- An upper level disturbance producing a tropospheric fold and subsequent SI.
  - Depicted in cross-sections or time-height cross-sections by sloping lines of PT, by 1-PVU or greater descending into the troposphere, and by an area of dry air.
- A well-mixed or even turbulent atmosphere resulting from an upper level disturbance and creating conditions for vertical movement of SI-air to the earth's surface.

Additionally, WDEQ/AQD is a member of a national EPA SI workgroup that was formed during 2012. The primary goal of the workgroup is to diagnose past SI events, including the June 6, 2012 event described in this document.

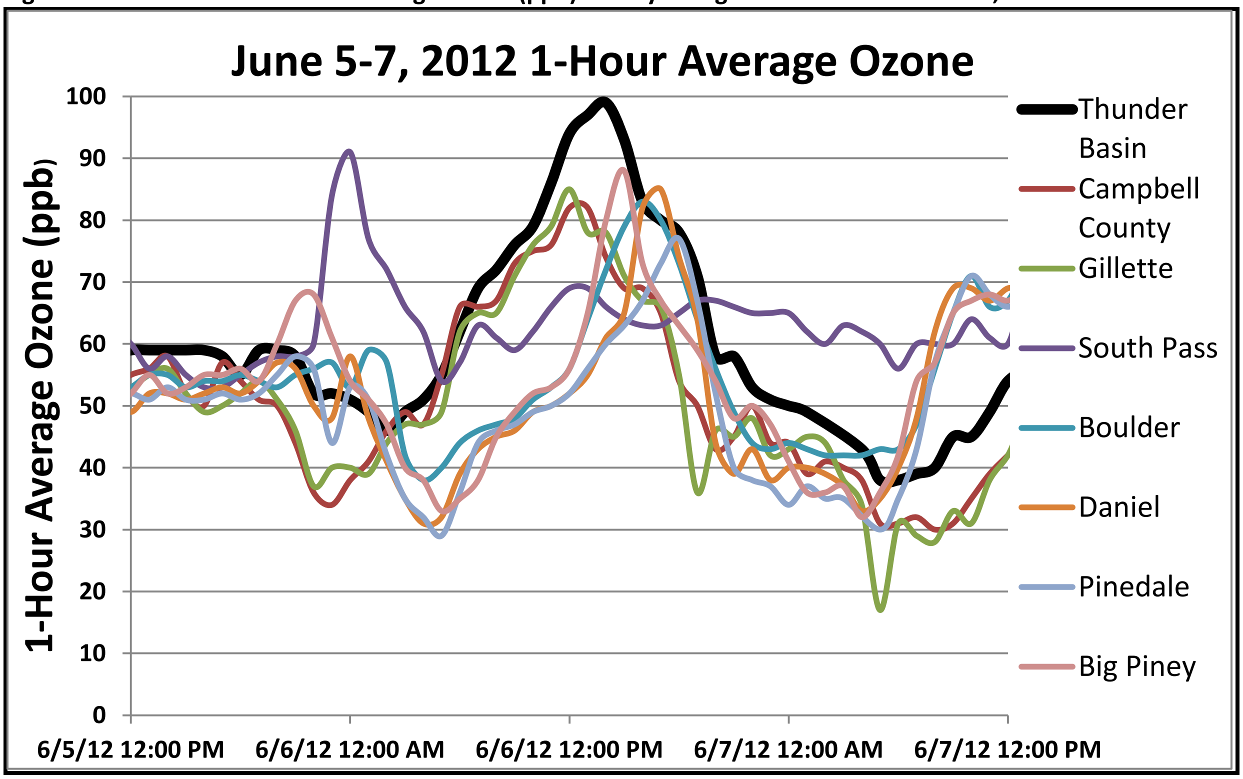
[11] Via the function capability of the Integrated Data Viewer (IDV), one can determine the ELR as follows: divide the temperature difference of the h7-h5 layer by the difference in height (distance) between the h7 and h5 pressure surface.

JUNE 6, 2012 EXCEPTIONAL EVENT

Summary

During June 6, 2012, an upper atmospheric disturbance associated with an SI moved over Wyoming creating elevated ozone readings resulting in an 8-hour ozone standard exceedance of 88 ppb at the Thunder Basin, Wyoming ozone monitor. Additionally, the ozone monitors at Gillette (approximately 30 miles south of Thunder Basin) and Campbell County (approximately 40 miles south of Thunder Basin) measured elevated 1-hour average values from the 70's to lower 80's ppb during the SI event (refer to Figure 5).

Figure 5. Time series of 1-hour average ozone (ppb) for Wyoming monitors from June 5-7, 2012.



Also during the June 6, 2012 SI event, the Upper Green River Basin (UGRB) ozone monitors at Boulder, Daniel, Pinedale, and Big Piney experienced elevated 1-hour average ozone values from the 70's to mid-80's ppb. Elevated ozone values typically occur at these monitors because of light winds and snow cover during the January-March winter ozone season. However, strong winds buffeted the UGRB prior to the SI event, and no snow cover was present on June 6, 2012.

Furthermore, the South Pass, Wyoming ozone monitor located at the southeastern tip of the Wind River Mountain Range in Fremont County, Wyoming, recorded a 1-hour average ozone value of 91 ppb at 12 am MST, June 6, 2012. Sited to monitor long-range transport of pollutant, the South Pass monitor is the highest elevation ambient air quality station in the WDEQ/AQD network at an elevation of 8289 feet (2526 meters) AMSL.

For the month of June from 2000 to 2012, Wyoming ground level, 1-hour average ozone levels at all ozone monitors ranged from 34-52 ppb (25-75% interquartile range) with a mean of 42.6

ppb. However, when an SI occurs, 8-hour average values [derived from the 1-hour average] can exceed 80 ppb on a time scale of a few hours to a few days (Mohnen and Reiter 1977). During June 6, 2012, Thunder Basin 8-hour average ozone was greater than 80 ppb for seven consecutive hours. At 2 pm MST on June 6, 2012, the Thunder Basin ozone monitor recorded the highest 1-hour average ozone value of 99 ppb, resulting in a daily maximum rolling 8-hour average of 88 ppb.

Public Notification and EPA's Air Quality System Data

Citizens of Wyoming have continuous access to WyVisNet via the internet, which serves as a means of public information dissemination regarding elevated ozone readings. WDEQ/AQD's Wyoming Visibility Monitoring Network (WyVisNet) website provided near real-time pollutant and meteorological data from Thunder Basin, South Pass, Boulder, Daniel, Campbell County, and Gillette and was operational during the June 6, 2012 elevated ozone event. Additionally, Thunder Basin, South Pass, Boulder, Daniel, Campbell County, and Gillette ozone data are also reported to the EPA's AIRNow website.

The public also has access to EPA's Air Quality System (AQS) database that houses validated data from the AQD's monitoring stations. The data displayed in Figure 5 was extracted from the AQS.

Data QA/QC and Equipment

Quality Assurance/Quality Control procedures were followed in accordance with 40 CFR Part 58, Appendix A, Section 3.2 *Measurement Quality Checks of Automated Methods* and the *Quality Assurance Project Plan* for the Thunder Basin monitoring project.

On April 14, 2012 and November 13, 2012 Technical & Business Systems, Inc., conducted independent performance audits of the ozone analyzer at Thunder Basin (refer to Table 2). All tests met WDEQ/AQD specified data quality objectives, which are consistent with QA Handbook Vol II, Section 3.0, Revision No: 1.

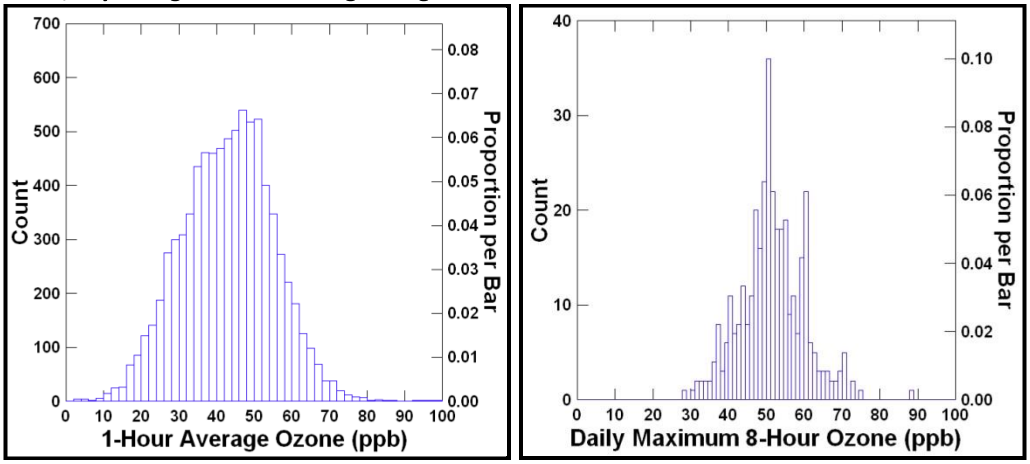
Table 2. Statistics for April 14 and November 13, 2012.

2012	**Thunder Basin Ozone Audit Results for 2nd and 4th Quarters 2012**			
	Slope	**Correlation**	**Y-Intercept**	**Audit Point % Difference**
April 14	0.983	1.0000	0.004	**Point 2=8.3%** **Point 3=3.8%** **Point 4=0.0%**
November 13	0.972	1.0000	0.002	**Point 2=2.7%** **Point 3=0.0%** **Point 4=-1.7%**

Statistical Analysis

A basic method for portraying the statistical significance of the June 6, 2012 elevated ozone event is with a histogram. A histogram shows the frequency of occurrence of individual values, and often it takes the shape of a "Bell Curve" or "normal distribution". Figure 6 shows the 1-hour average and daily maximum 8-hour ozone for the Thunder Basin, Wyoming ozone monitor for each June from 2001-2012. Note that the bell curve is elongated to the right where the June 6, 2012 Thunder Basin elevated ozone concentrations reside. The extension of the bell curve to the right represents data of statistical significance.

Figure 6. June 2001- 2012 Histogram of 1-hour average and daily maximum 8-hour ozone values for Thunder Basin, Wyoming. Click to enlarge images.



An additional statistical measure of significance for the June 6, 2012 Thunder Basin elevated ozone event is a simple t-test[12] between the two means. A high t-test score and very low p-value[13], shown in Table 3, indicate that the June 6, 2012 time period was statistically significantly higher when compared to ozone values observed over the month of June 2001-2012.

If one analyzes the June 6, 2012 event from a cumulative percentage perspective, the Thunder Basin daily maximum 8-hour average ozone value of 88 is the highest value recorded for June 2001-2012 (refer to Table 4).

Table 3. Thunder Basin t-test and p-value statistics for 1-hour average ozone statistics for Junes 2001-2012.

Dates	**Statistic**		
	Number of Samples	**Arithmetic Mean**	**Standard Deviation**
June 2001-2012	8,144	42.45	12.08
Thunder Basin June 6, 2012	8	88.88	7.85
	t-test=16.74	p-value=0.0000	

Table 4. Thunder Basin 99th and greater percentile for Junes 2001-2012.

Site	**Daily 8-Hour Maximum Ozone**	**Count**	**Cumulative Percent**
Thunder Basin	88	1	100.0000

[12] For further information on t-tests, please consult: http://www.statsoft.com/textbook/basic-statistics/#t-test for independent samples. Note to reader: the WDEQ does not endorse any private business or its products. The aforementioned site is for informational purposes only.

[13] For further information on p-values, please consult: http://www.statsoft.com/textbook/elementary-concepts-in-statistics/#What is "statistical significance" (p-level). Note to reader: the WDEQ does not endorse any private business or its products. The aforementioned site is for informational purposes only.

Finally, another way to display the June 6, 2012 Thunder Basin elevated ozone values as being statistically significantly higher is to use a “box-and-whisker” plot. Figure 7 shows how to interpret a “box-and-whisker” plot. Figure 8 shows that the June 6, 2012 1-hour average and daily 8-hour maximum ozone concentrations are statistical outliers when compared to all Thunder Basin ozone values observed during the month of June 2001-2012.

Figure 7. Description of how to interpret a Box-and-Whiskers plot (Image courtesy Sonoma Technology, Inc.). Click image to enlarge.

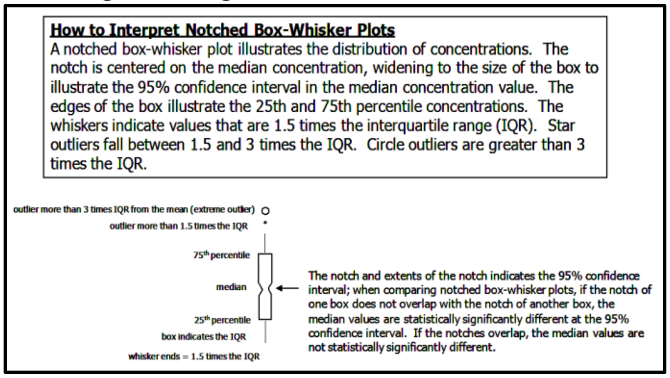
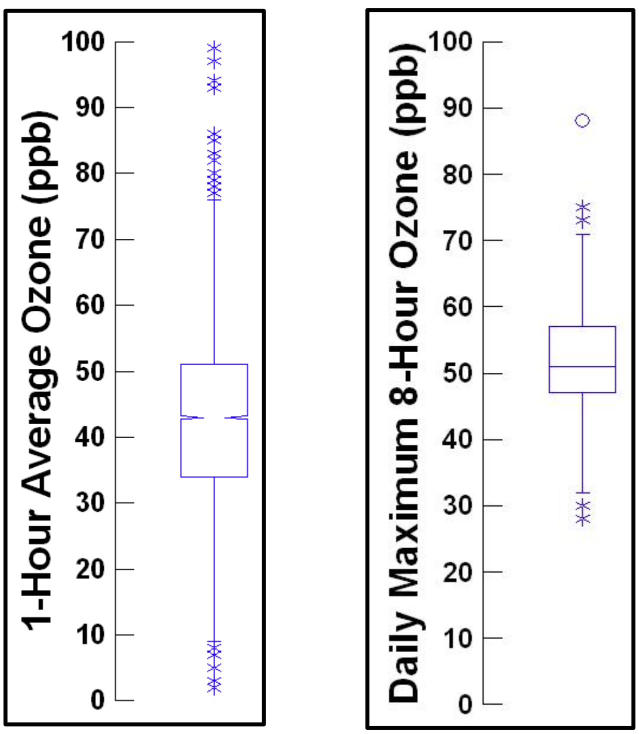


Figure 8. Box-and-whiskers plot of Junes 2001-2012 for Thunder Basin. Click images to enlarge.



Supporting Meteorological Data: Weather Overview

The NARR depicts[14] a vigorous upper level disturbance over Nevada at 5 am MST on June 5, 2012 (refer to Figure 9). By 11 pm MST on June 5, 2012, the disturbance had moved from Nevada to western Wyoming (refer to Figure 10). As shown by Figures 9 and 10, the upper level disturbance was directly upstream of the affected Wyoming ozone monitors prior to the increase in 1-hour average ozone during June 6, 2012.

Figure 9. North America Reanalysis valid at 5 am MST, June 5, 2012. Click image to enlarge. Click [here] for a time animation 500 mb heights and relative vorticity for June 5-6, 2012.

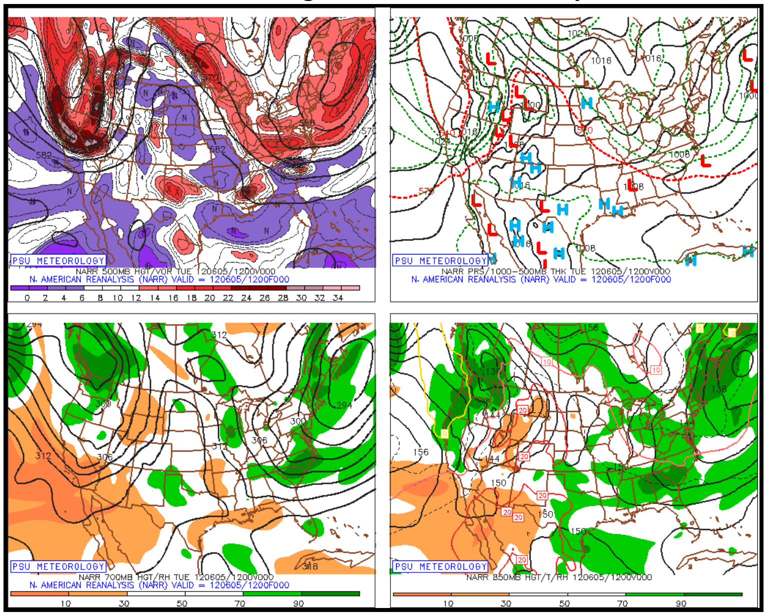
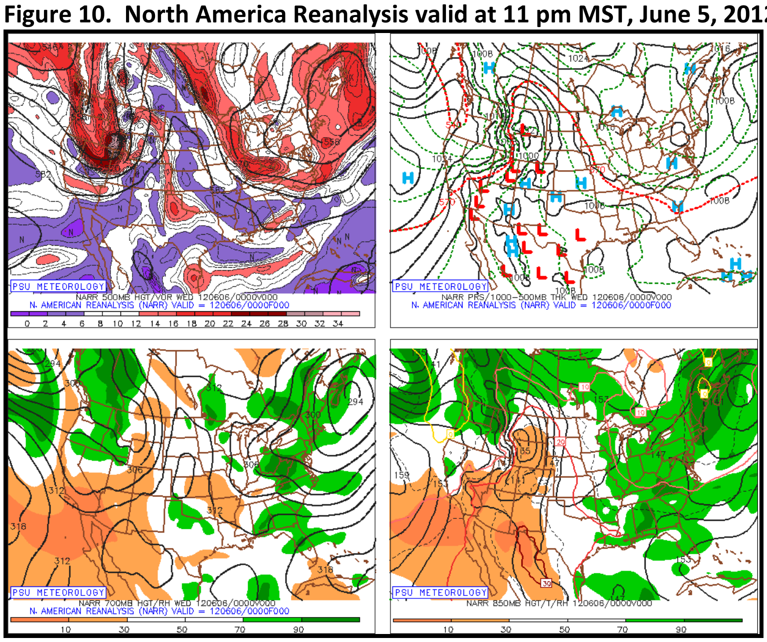


Figure 10. North America Reanalysis valid at 11 pm MST, June 5, 2012. Click image to enlarge.



[14] Please refer to Appendix D to learn how to interpret the NARR.

Supporting Meteorological Data: GOES Total Column Ozone Data

Because of the upper air disturbance and attendant SI, an enhanced green/red area (increased Dobson values) can be seen in the hourly GOES total column ozone data to the west of Wyoming (refer to Figure 11) at 4 pm MST, June 4, 2012. Figures 11 and 12 show the eastward movement of the upper level storm system and the associated higher Dobson values by 3 pm MST, June 6, 2012 and provide additional evidence of an SI event that affected Wyoming. (Note to reader: GOES Band-12 data was unavailable during this time).

Figure 11. GOES Total Column Ozone (DU) for 4 pm MST June 4, 2012. Click to image to enlarge. Image courtesy of the Data Center at the Space Science and Engineering Center (SSEC) of the University of Wisconsin – Madison. Click here for a time animation of GOES TCO for June 4-6, 2012.

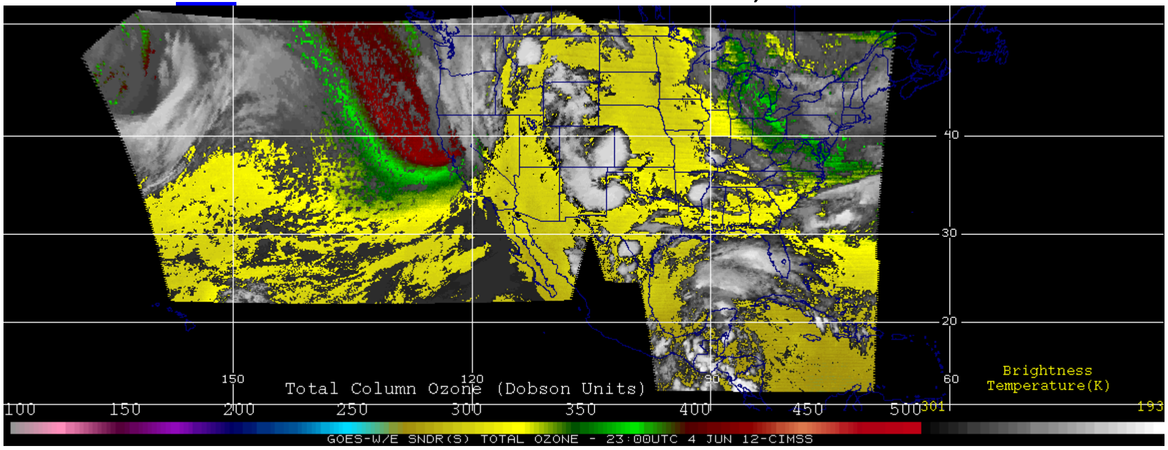
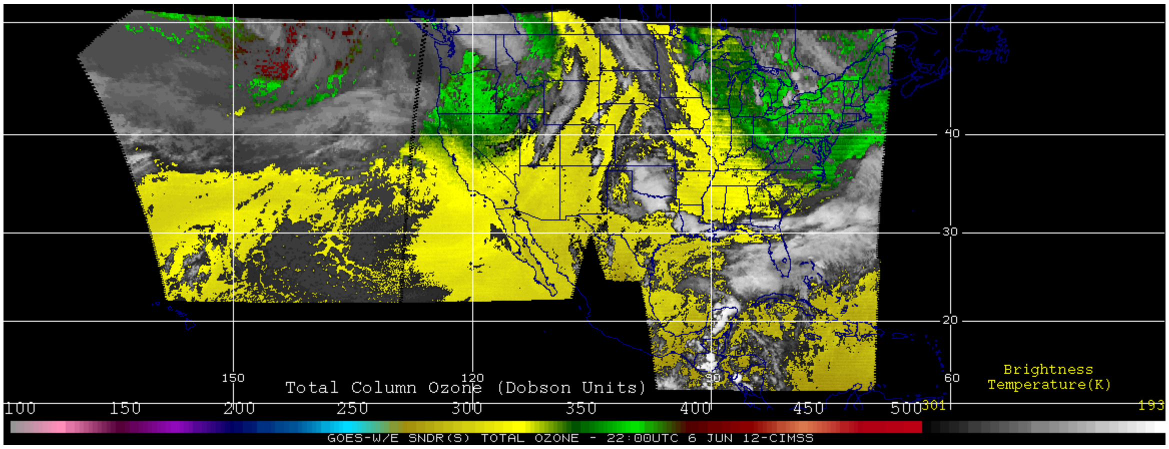


Figure 12. GOES Total Column Ozone (DU) for 3 pm MST June 6, 2012. Click to Image to enlarge. Image courtesy of the Data Center at the Space Science and Engineering Center (SSEC) of the University of Wisconsin – Madison.



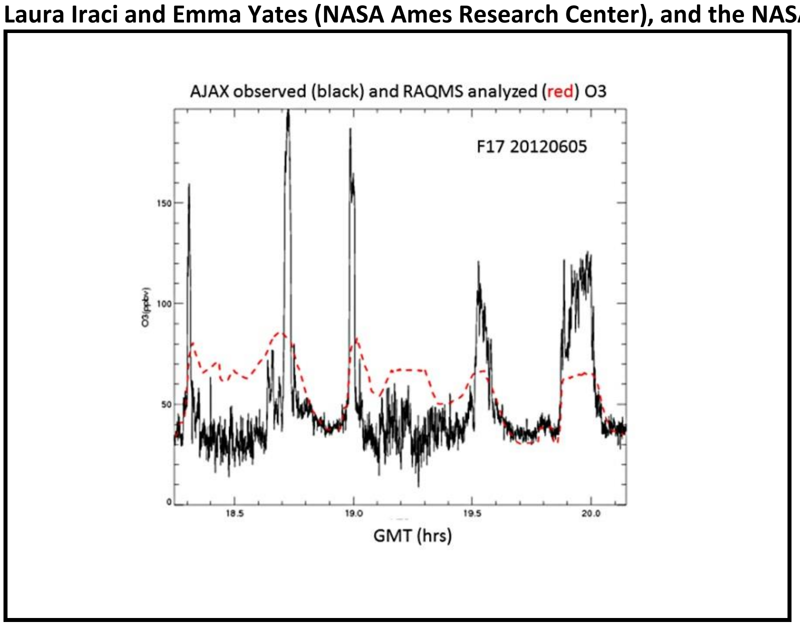
Supporting Meteorological Data: Research Flight Ozone Measurements Coupled With a Realtime Air Quality Modeling System

Recall that stratospheric air can be "tagged" by identifying areas characterized by approximately greater than or equal to 1-PVU, dry air, and tightly packed, sloping isolines of PT. One means of showing the relationship between IPV and ozone is by using a combination of model analyses of ozone, IPV, and real-time measurements of ozone within a tropospheric fold.

Between 11 am and 1 pm MST, June 5, 2012, NASA's Alpha Jet Atmospheric eXperiment (AJAX) Flight 47 flew through an SI associated with a tropospheric fold over California, which eventually resulted in elevated ozone over Wyoming. Equipped with an ozone monitor, the flight measured ozone concentrations as it traversed the tropospheric fold. Figure 13 displays the flight's ozone data (denoted by black line) plotted over time. The Realtime Air Quality Modeling System (RAQMS)[15] model analysis of ozone is shown by the dashed red line in Figure 13. Note that the model under predicts ozone concentrations compared to the flight data.

Figure 14 shows the RAQMS model analysis (valid 11 am MST, June 5, 2012) of ozone at 4 km msl and the Flight 47 flight path over western California (upper panel of Figure). The bottom panel of Figure 14 is a vertical cross-section showing the Flight 47 altitude and the RAQMS ozone analysis along 122º W longitude. Figure 15 is the same as Figure 14 except that IPV is portrayed in the Figure. Figures 14-15 clearly show that Flight 47 intersected a portion of the tropospheric fold/SI. Similar to the April 28, 2008 START08 research flight mentioned in Appendix A of "Documented SI's", the AJAX Flight 47 flight data clearly show a maximum in ozone concentration coincident with the tropospheric fold between 4 and 4.5 km msl.

Figure 13. Time series of insitu (black) and RAQMS analysed (dashed red) O_3 (ppbv) along AJAX Flight 47 track on June 5, 2012. Figure courtesy of Brad Pierce (NOAA/NESDIS Center for Satellite Applications and Research), Laura Iraci and Emma Yates (NASA Ames Research Center), and the NASA Air Quality Applied Sciences Team.



[15] For more information on RAQMS, please visit this website: http://raqms-ops.ssec.wisc.edu/.

Figure 14. RAQMS 4km O_3 (ppbv, upper panel) map and 122°W cross-section (ppbv, lower panel) on June 5, 2012 at 11 am MST. The aircraft flight track is shown in black. Note the tropopause fold indicated by the tongue of high ozone extending from the lower stratosphere into the mid-troposphere. Figure courtesy of Brad Pierce (NOAA/NESDIS Center for Satellite Applications and Research), Laura Iraci and Emma Yates (NASA Ames Research Center), and the NASA Air Quality Applied Sciences Team.

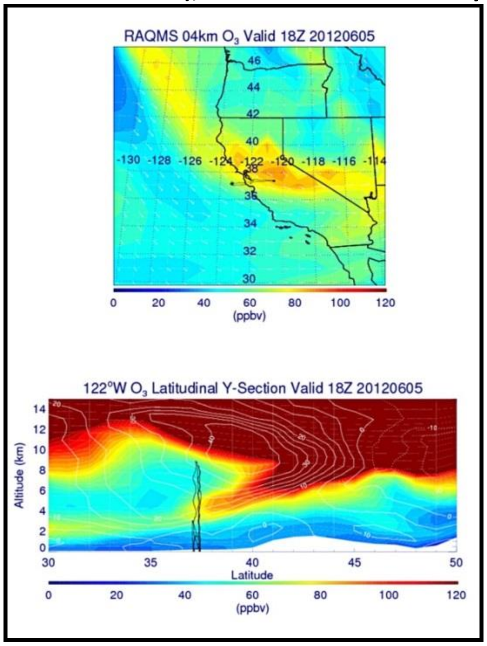
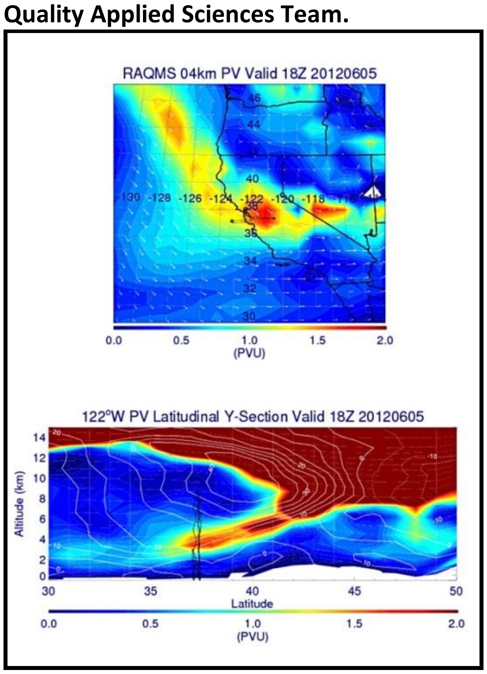
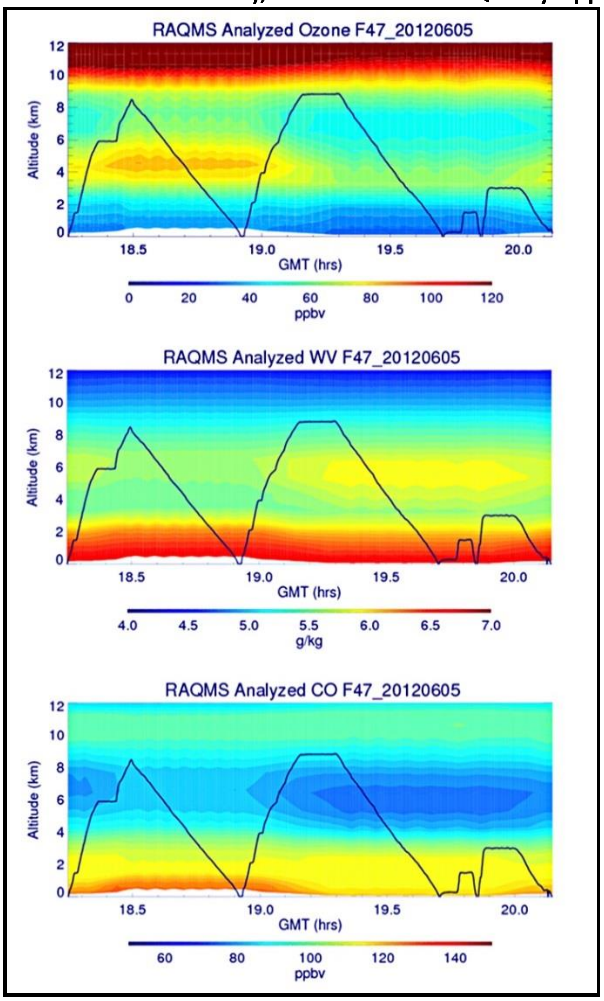


Figure 15. RAQMS 4km Isentropic Potential Vorticity (IPV) (PVU, upper panel) map and 122°W cross-section (PVU, lower panel) on June 5, 2012 at 11 am MST. The aircraft flight track is shown in black. Note the tropopause fold indicated by the tongue of relatively strong potential vorticity extending from the lower stratosphere into the mid-troposphere. Figure courtesy of Brad Pierce (NOAA/NESDIS Center for Satellite Applications and Research), Laura Iraci and Emma Yates (NASA Ames Research Center), and the NASA Air Quality Applied Sciences Team.



RAQMS analysis of ozone, water vapor, and CO along with the Flight 47 flight time and altitude are shown in Figure 16. The upper panel of Figure 16 is comparable to Figure 13 in terms of model analysis of ozone versus Flight 47 ozone data. The middle and lower panels of Figure 16 show a dry air layer coincident with smaller values of CO; another indicator of stratosphere air's presence in the troposphere.

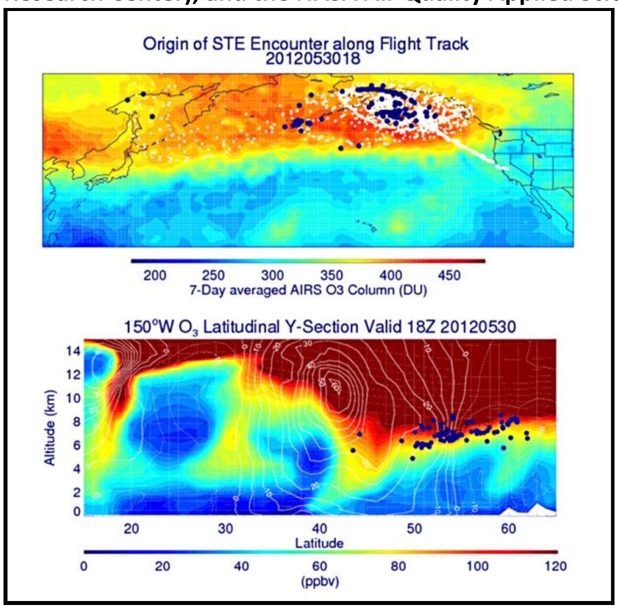
Figure 16. RAQMS analysed O_3 (ppbv, upper panel), water vapor (g/kg, middle panel) and CO (ppbv, lower panel) along AJAX Flight 47 track on June 5, 2012. AJAX flight track altitude is shown in black. Figure courtesy of Brad Pierce (NOAA/NESDIS Center for Satellite Applications and Research), Laura Iraci and Emma Yates (NASA Ames Research Center), and the NASA Air Quality Applied Sciences Team.



Supporting Meteorological Data: SI Origin Using Trajectories and Satellite Measurements

The genesis of the tropospheric fold and subsequent SI can be traced back to the Gulf of Alaska. The upper panel of Figure 17 shows backward trajectory endpoints (white) beginning at the Flight 47 path, and ending on May 30, 2012. The starting point of forward trajectories on May 30, 2012 and ending at the Flight 47 path is shown by the blue dots. Superimposed on the trajectory history is the 7-day averaged (May 30-June 5, 2012) AIRS[16] satellite total column ozone data in the upper panel of Figure 17. RAQMS analysis of ozone along 150º W combined with the origin of the forward trajectories on May 30, 2012 is depicted in the bottom panel of Figure 17. Based on trajectory analysis (to/from the Flight 47 path) and TCO, the most likely beginning of the tropospheric folding event was over the Gulf of Alaska.

Figure 17. Upper panel shows a map of 7-day averaged (May 30-June 5, 2012) AIRS total column O_3 (DU) with back trajectory history (white) and origin (white with blue edges) at 11 am MST on May 30, 2012 for AJAX Flight 47 SI encounter. Lower panel shows RAQMS 150°W O_3 (ppbv) and zonal wind (m/s) cross-section with origin of AJAX Flight 47 SI encounter (blue dots) at 11 am MST on May 30, 2012. Figure courtesy of Brad Pierce (NOAA/NESDIS Center for Satellite Applications and Research), Laura Iraci and Emma Yates (NASA Ames Research Center), and the NASA Air Quality Applied Sciences Team.



As mentioned in the introduction of this package, stratosperhic air contains little CO (Pan, Randel, et al. 2004; Newell, et al. 1999; Stoller, et al. 1999). AIRS satellite measurements of CO at 618 mb (approximate level of the SI) show lower CO concentrations over California on June 5, 2012 (refer to Figure 18). When combined with Figures 13-17, the AIRS data suggest that the lower CO concentrations over California were associated with the location of stratospheric air on June 5, 2012 (Fight 47 day). Figure 18 depicts higher CO concentrations over Wyoming on June 5, 2012 as well. However, the concentration of CO over Wyoming decreased (at 618 mb) on June 6, 2012 (day of elevated Wyoming ozone) as shown by Figure 19. The AIRS CO data provides further evidence of an SI having moved from the southwestern United States to Wyoming.

[16] For more information on AIRS satellite data, please visit this website: http://airs.jpl.nasa.gov/.

Additionally, WDEQ/AQD is a member of a national EPA SI workgroup that was formed during 2012. The primary goal of the workgroup is to diagnose past SI events, including the June 6, 2012 event described in this document. The SI workgroup concluded that the June 6, 2012 elevated ozone event was not caused by transport (ozone and/or ozone precursors) from Asia based on the aforementioned discussion regarding trajectories and CO concentrations.

Figure 18. AIRS satellite derived CO at 618 mb (descending pass) for June 5, 2012. Figure via Patrick Reddy (Colorado Department of Public Health and Environment) and courtesy the Giovanni online data system, developed and maintained by the NASA GES DISC.

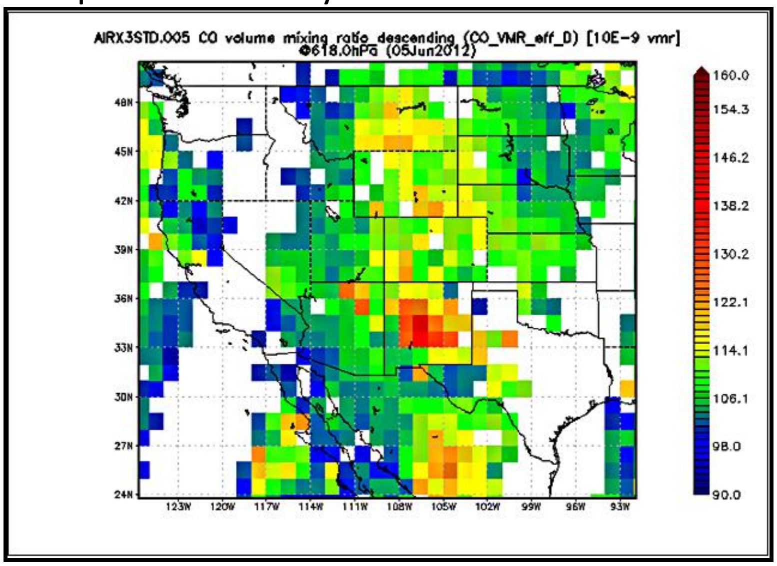
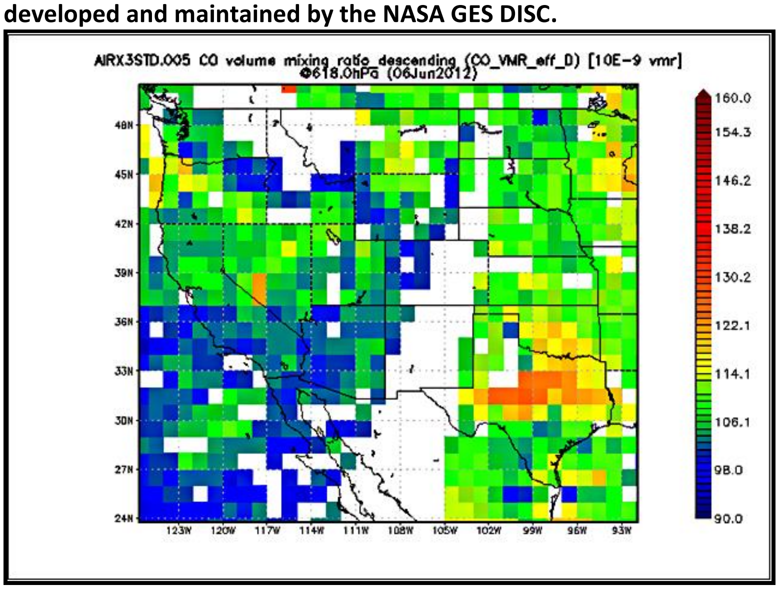


Figure 19. AIRS satellite derived CO at 618 mb (descending pass) for June 6, 2012. Figure via Patrick Reddy (Colorado Department of Public Health and Environment) and courtesy the Giovanni online data system, developed and maintained by the NASA GES DISC.



Supporting Meteorological Data: Time-Height Cross-Sections and Cross-Section of IPV, RH, and PT

The SI signature also appears in the 13-km RAP data from June 6, 2012. With the SI upstream of Wyoming and the upper level storm system moving toward Wyoming, the logical choice for a time-height cross-section was northern Utah (refer to Figure 20). An IPV time-height cross-section over northern Utah shows the descending 1-PVU isoline, the “pocket” of dry air, and the sloping isolines of potential temperature having occurred during June 5-6, 2012 (Figures 21-23 respectively).

Figure 20. Northern Utah location (black square) of time-height cross-section of IPV from 3 am MST, June 3 and ending at 3 pm MST, June 7, 2012.

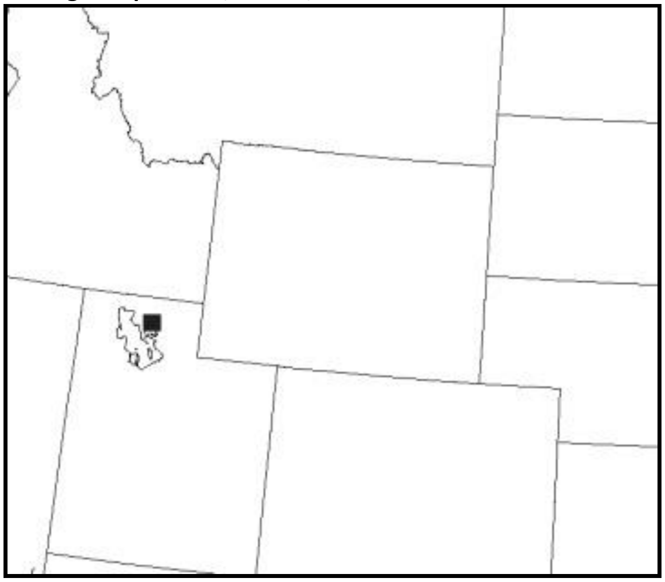


Figure 21. Northern Utah time-height cross-section of IPV from 3 am MST, June 3 and ending at 3 pm MST, June 7, 2012. Format of date and time is Day/Time. Click image to enlarge.

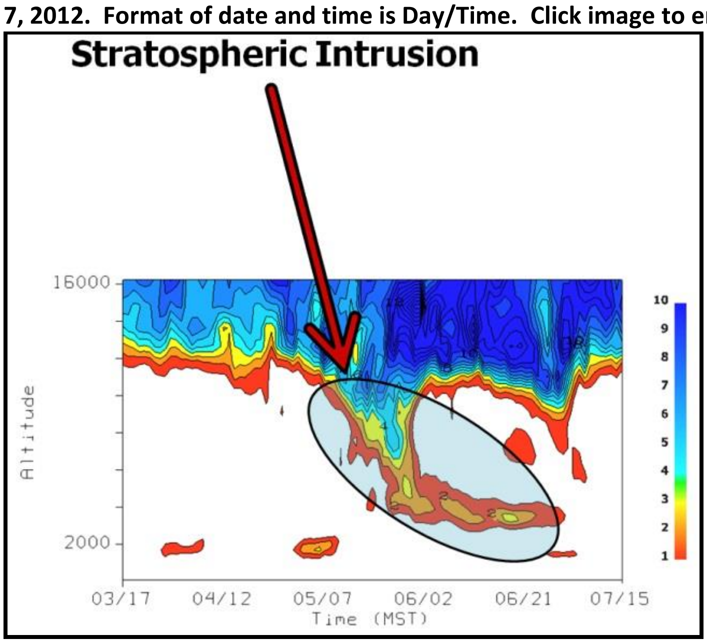


Figure 22. Northern Utah time-height cross-section of Relative Humidity from 3 am MST, June 3 and ending at 3 pm MST, June 7, 2012. . Format of date and time is Day/Time. Click image to enlarge.

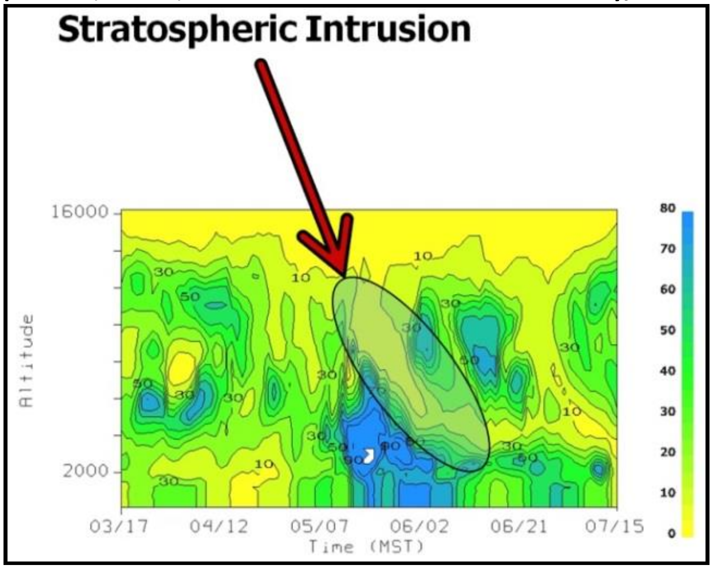
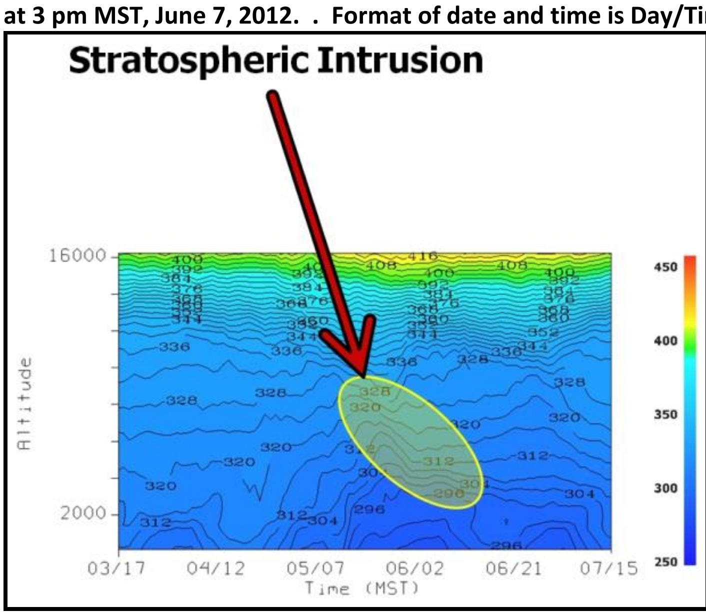


Figure 23. Northern Utah time-height cross-section of Potential Temperature from 3 am MST, June 3 and ending at 3 pm MST, June 7, 2012. . Format of date and time is Day/Time. Click image to enlarge.



Using the 13-km RAP model 0-hour analyses, a descending SI can be illustrated by examining atmospheric vertical cross-sections over a time range. One can visualize an SI approaching the earth's surface by observing the temporal and vertical evolution of the greater than 1-PVU isoline, dry air, and the pattern of PT isolines superimposed on a cross-section of the earth's terrain.

Remember that the South Pass ozone monitor experienced a 1-hour average ozone value of 91 ppb at 12 am, June 6, 2012. One can visualize the descending SI over the South Pass monitor during the nighttime hours by cross-section analysis. Figure 24 shows the line used to create a north-south cross-section over Wyoming. As the upper level system moved toward Wyoming during June 5-6, 2012, an SI descended (as shown by the descending red isoline of greater than 1-PVU, less than 15% RH area, and sloping PT isolines) over the South Pass ozone monitor as depicted by Figures 25-26. Note that less than 15% relative humidity air and tightly packed isolines of PT coincide with the descending 1-PVU red isoline throughout June 5-6, 2012.

Figure 24. Map view of terrain, IPV, RH, and PT cross-section.

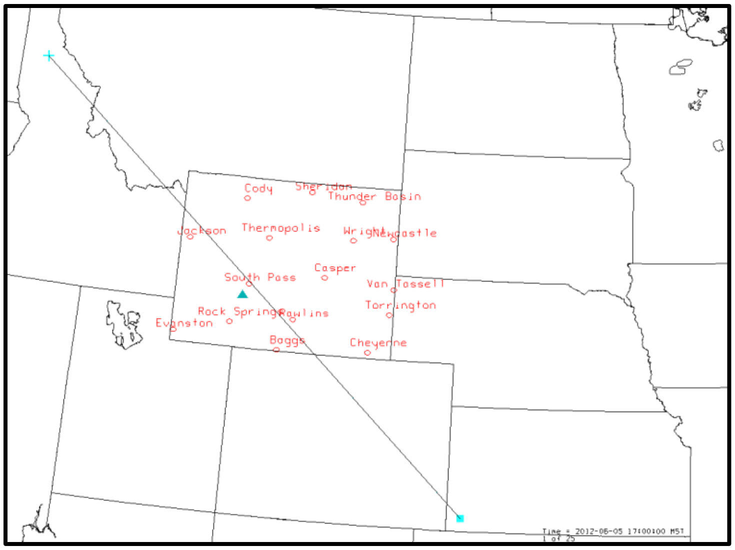


Figure 25. RAP 13-km, 0-hour analysis showing south-to-north cross-section (left-to-right) terrain (solid dark line), IPV (colored contours starting at 1-PVU), RH (shaded areas depicting RH values less than 15%), and PT (thin black contours) cross-section valid at 11 pm MST, June 5, 2012. Click image to enlarge. Click [here] for a time animation from 5 am MST June 13 to 11 am MST June 14, 2012.

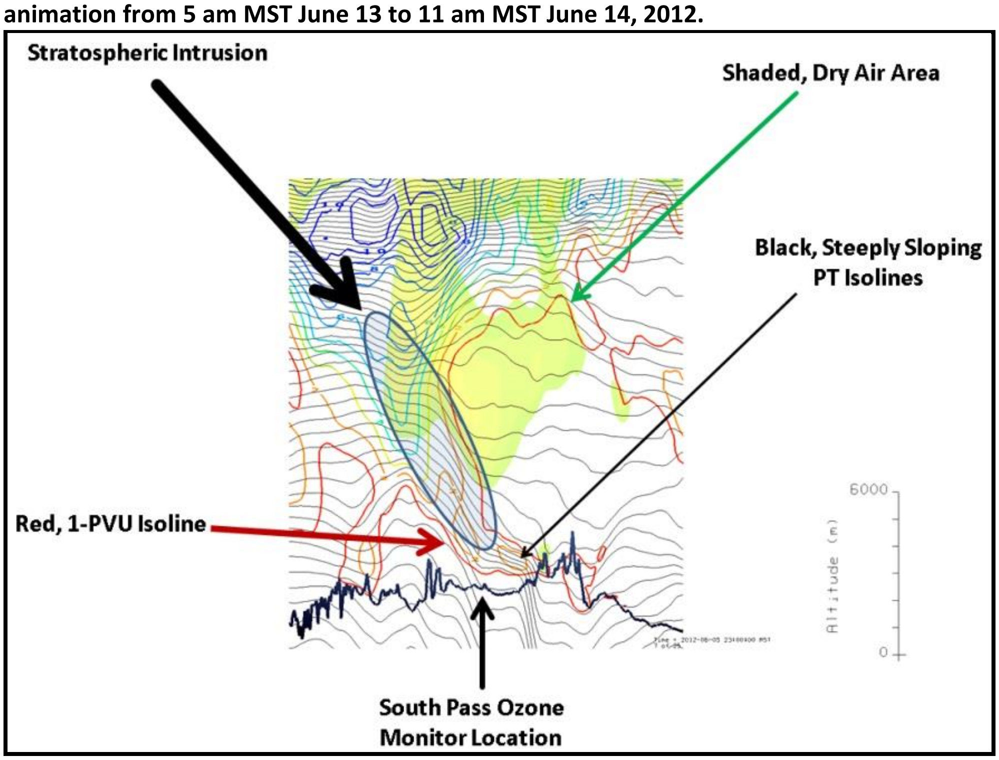
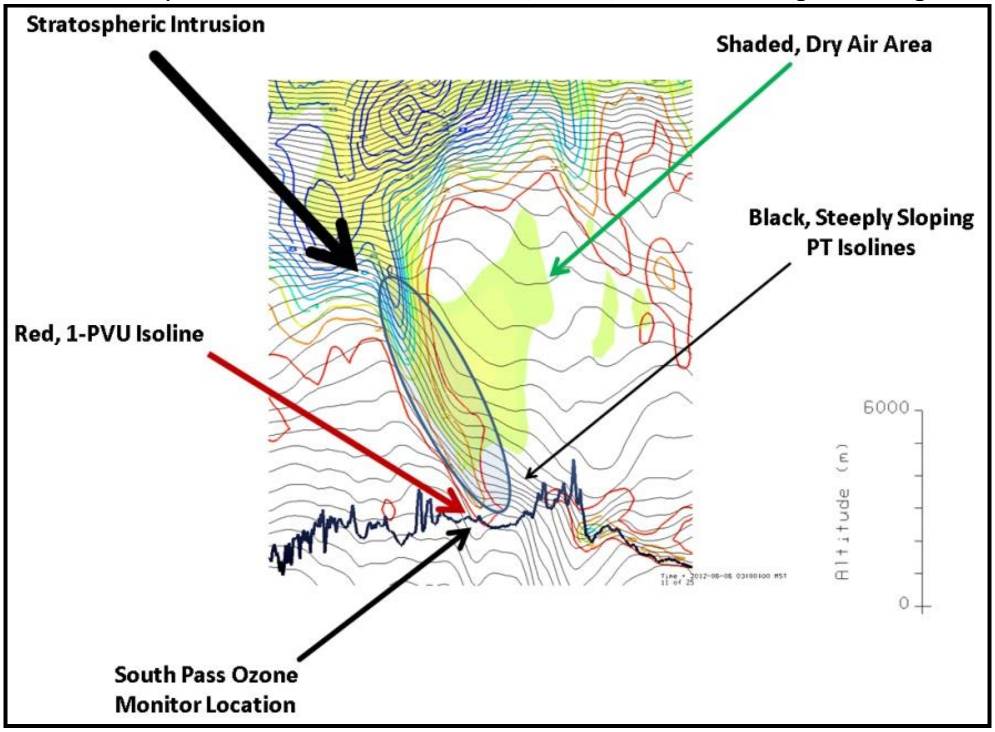


Figure 26. RAP 13-km, 0-hour analysis showing south-to-north cross-section (left-to-right) terrain (solid dark line), IPV (colored contours starting at 1-PVU), RH (shaded areas depicting RH values less than 15%), and PT (thin black contours) cross-section valid at 3 am MST, June 6, 2012. Click image to enlarge.



Supporting Meteorological Data: SI-Composite Chart

Another way of showing the SI event is by showing an “SI composite chart” of IPV, RH, and surface-based ozone. This “quick look chart” is an easy way to visualize IPV, RH, and surface-based ozone on one chart. Figure 27 shows the 0-hour NAM-12 analysis of the 500 mb height pattern, values greater than 1.5-PVU, and relative humidity areas less than or equal to 10% at 600 mb (approximate height of the SI) valid at 11 am MST, June 5, 2012. Superimposed on the chart is EPA’s AQS daily maximum 8-hour ozone greater than 65 ppb. Figure 28 displays the same aforementioned parameters valid at 11 am MST, June 6, 2012. The noteworthy aspect of the “SI composite chart” is that at 11 am MST, June 6, 2012, all of the parameters are juxtaposed on one another. Specifically, the greater than 1.5-PVU area corresponds with RH values less than or equal to 10% aiding in producing the greater than 65 ppb maximum (“bulls-eye”) over northeastern Wyoming. The chart also shows elevated IPV and low RH over the UGRB where elevated ozone concentrations were also recored. The “SI composite chart” provides further evidence of an SI causing an increase in surface-based ozone.

Figure 27. 11 am MST, June 5, 2012 NAM-12 analysis of 500 mb heights in meters, 600 mb IPV >= 1.5 PVUs in blue, 600 mb RH <= 10% in grey, and EPA AQS Daily Max 8-hour O3 in ppb >= 65 ppb in rainbow contours and shading. Figure courtesy Patrick Reddy (Colorado Department of Public Health and Environment).

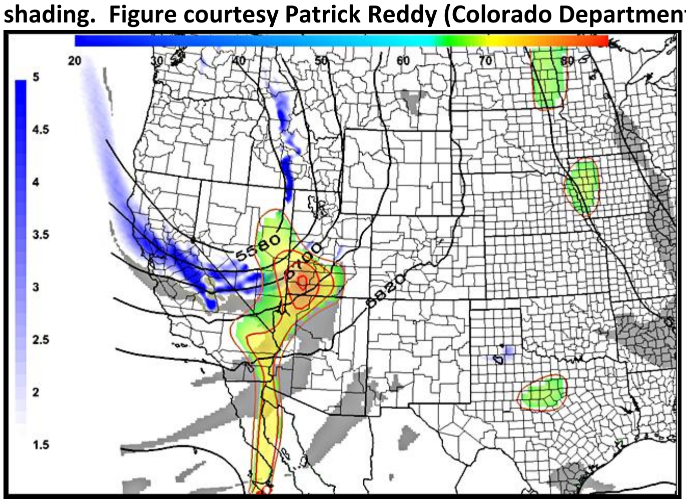
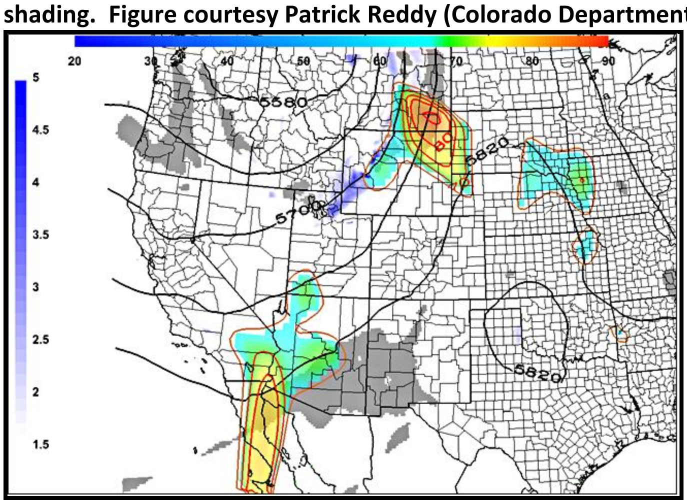


Figure 28. 11 am MST, June 6, 2012 NAM-12 analysis of 500 mb heights in meters, 600 mb IPV >= 1.5 PVUs in blue, 600 mb RH <= 10% in grey, and EPA AQS Daily Max 8-hour O3 in ppb >= 65 ppb in rainbow contours and shading. Figure courtesy Patrick Reddy (Colorado Department of Public Health and Environment).



Supporting Meteorological Data: Upper Air RAOB's

The upper level disturbance and SI signature are evident on the upper air soundings from June 5-6, 2012 at Salt Lake City, Utah and at Riverton, Wyoming. The tropopause at 5 pm MST, June 5, 2012 at Salt Lake City was located at 525 mb (refer to Figure 29). At 5 am MST, June 6, 2012, the tropopause was approximately at the 650 mb level at Salt Lake City (Figure 30). During the same period, the 5 pm MST, June 5, 2012 Riverton sounding showed the tropopause at the 430 mb level (Figure 31). 12 hours later, at 5 am MST, June 6, 2012, the RAOB showed the tropopause had lowered to the 700 mb level (Figure 32). At 5 pm on June 6, 2012, the Riverton sounding portrayed the tropopause at the 620 mb level (Figure 33).

Recall that a lowering of the tropopause is another indication of a tropospheric fold. As the upper level disturbance moved over western Wyoming during the early morning hours of June 6, 2012, the tropopause lowered from 430 mb to 700 mb at Riverton. A dry adiabatic lapse rate (DALR) existed on the 5 pm MST, June 6, 2012 sounding at Riverton representing a well-mixed lower-to-mid troposphere providing further evidence that the SI was able to mix vertically to the ground.

Figure 29. Salt Lake City, Utah RAOB at 5 pm MST, June 5, 2012. Click image to enlarge. Image courtesy Plymouth State University Department of Atmospheric Science & Chemistry.

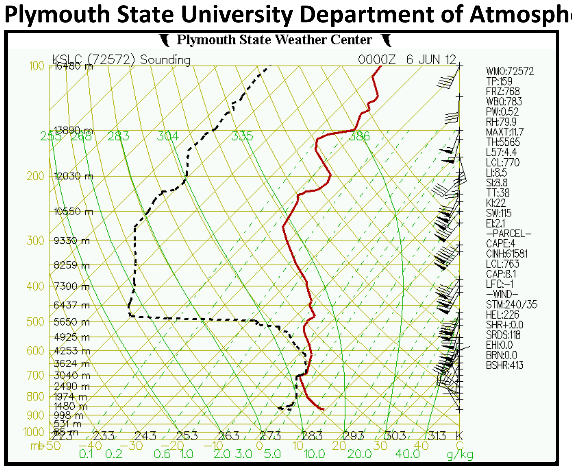


Figure 30. Salt Lake City, Utah RAOB at 5 am MST, June 6, 2012. Click image to enlarge. Image courtesy Plymouth State University Department of Atmospheric Science & Chemistry.

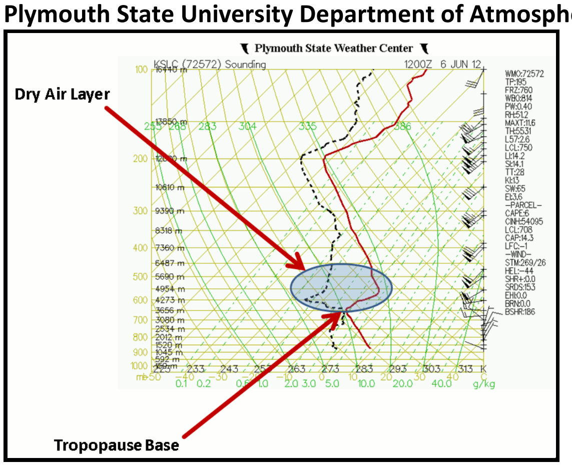


Figure 31. Riverton, Wyoming RAOB at 5 pm MST, June 5, 2012. Click image to enlarge. Image courtesy Plymouth State University Department of Atmospheric Science & Chemistry.

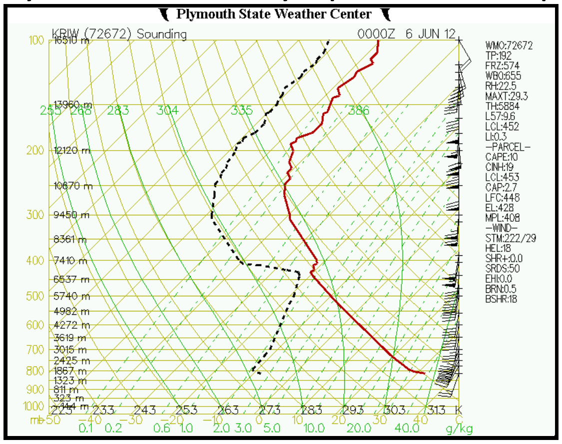


Figure 32. Riverton, Wyoming RAOB at 5 am MST, June 6, 2012. Click image to enlarge. Image courtesy Plymouth State University Department of Atmospheric Science & Chemistry.

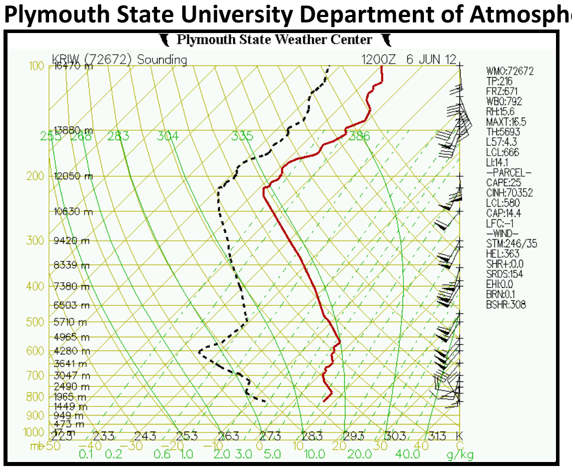
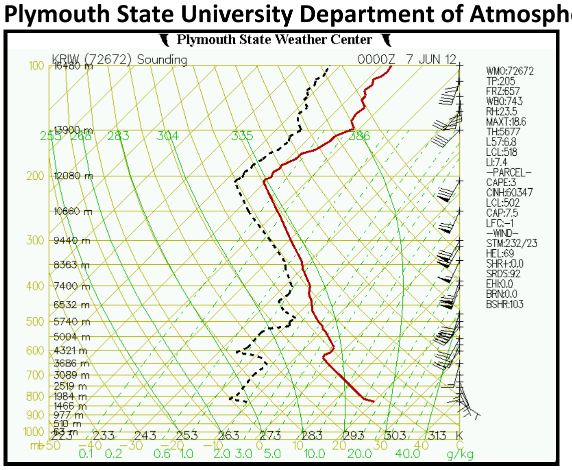


Figure 33. Riverton, Wyoming RAOB at 5 pm MST, June 6, 2012. Click image to enlarge. Image courtesy Plymouth State University Department of Atmospheric Science & Chemistry.



Supporting Meteorological Data: Vertical mixing as shown by lapse rates and boundary layer depth

An additional method for depicting a well-mixed atmosphere supportive of vertically transporting stratospheric ozone via an SI to the earth's surface is by means of a mid-tropospheric lapse rate analysis. By showing the juxtaposition of 750-550 mb environmental layer lapse rates (ELR's) and greater than 1-PVU at 650 mb, one can visualize conditions conducive for vertical mixing up to the SI. As the ELR starts to approach the DALR, the atmosphere is better able to mix in the vertical. Figure 34 shows an axis (blue isolines) of greater than 1-PVU from southwest to northeast Wyoming at 10 am MST, June 6, 2012 superimposed on ELR's ranging from 4-6º C km^{-1}. At 2 pm MST, June 6, 2012, Figure 35 shows the greater than 1-PVU axis remaining over the same area as the ELR's depicted increase to between 6-8 º C km^{-1}. From mid-morning to mid-afternoon of June 6, 2012, the ELR increased in magnitude and assisted the ozone-rich air to reach the vicinity of the Thunder Basin monitor. As a result, the Thunder Basin ozone monitor recorded a 1-hour average ozone value of 99 ppb at 2 pm MST.

Figure 34. 750-550 mb lapse rate and 650 mb IPV image at 10 am MST, June 6, 2012. Lapse rate units are degrees C km-1. IPV units are potential vorticity units. Click image to enlarge.

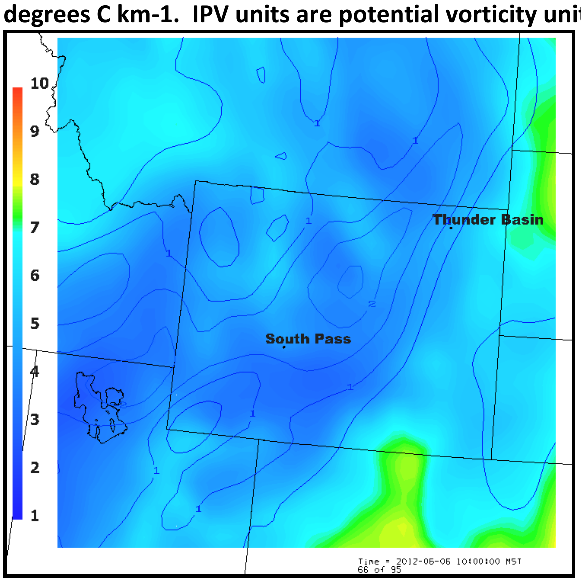
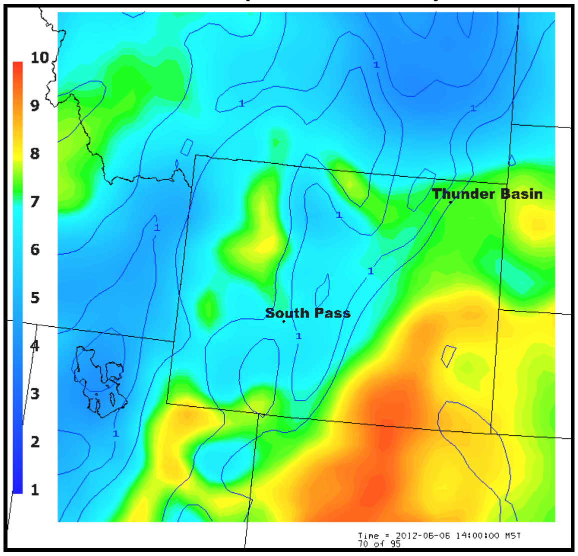


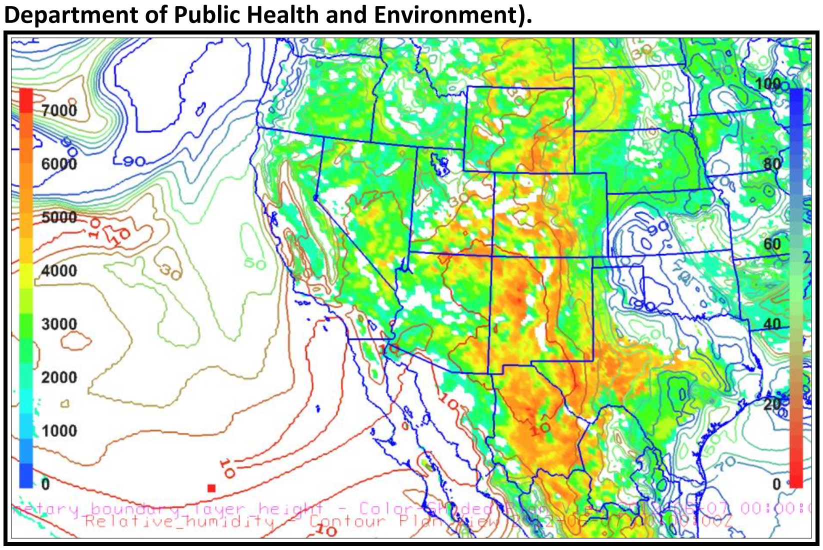
Figure 35. 750-550 mb lapse rate and 650 mb IPV image at 2 pm MST, June 6, 2012. Lapse rate units are degrees C km-1. IPV units are potential vorticity units. Click image to enlarge.



Another way to portray the atmosphere's ability to mix vertically is by showing the depth of the boundary layer (i.e. the well-mixed layer near the earth's surface) superimposed on 600 mb relative humidity. Remember that dry air is associated with an SI, and the 600 mb level is the approximate level of the SI as it passed over Wyoming.

As the depth of the boundary layer increases, the greater the chance for the atmosphere to mix the dry air at the 600 mb level to the earth's surface. Figure 36 shows the 600 mb level relative humidity (isolines) and the depth of the boundary layer in meters above ground. Note that the boundary layer depth at 5 pm MST, June 6, 2012 (as shown by the NAM-12 analysis) is between 3000-5500 meters agl and coincides with an area of relative humidity of less than 30 percent from southwest to northeast Wyoming. This is further evidence of ozone rich air from the SI being able to mix to the ground.

Figure 36. 600 mb planetary boundary layer depth (color-shaded, units in magl) and relative humidity (colored isolines) from the NAM-12 analysis run for June 6, 2012 at 5 pm MST. Figure courtesy Patrick Reddy (Colorado Department of Public Health and Environment).



Supporting Meteorological and Ambient Data: Surface-based data

Figures 37-38 show the June 5-7, 2012 1-hour average ozone and hourly relative humidity data for the Thunder Basin and South Pass (refer to Appendix C for Boulder, Campbell County, Gillette, Daniel and Pinedale data). The data shows a decrease in relative humidity that coincided with an increase in 1-hour average ozone values. Recall that air of stratospheric origin has small relative humidity values. Therefore, an increase in ozone concentration and a decrease in relative humidity at Thunder Basin and South Pass is further evidence of an SI event having occurred on June 6, 2012.

It has been documented (T. S. ENVIRON 2008) that elevated ozone values can occur at the UGRB ozone monitors of Boulder, Big Piney, Pinedale, and Daniel because of light winds, snow cover, and strong inversions during the January-March winter ozone season. However, during the June 6, 2012 period of elevated ozone, strong winds (refer to Figure 39) buffeted the UGRB prior to the SI event, and no snow cover or strong inversions were present. Accumulation of surface-based ozone precursors did not occur because meteorological conditions were not supportive of precursor buildup prior to elevated ozone readings.

Figure 37. June 5-7, 2012 Thunder Basin 1-Hour average ozone and hourly relative humidity.

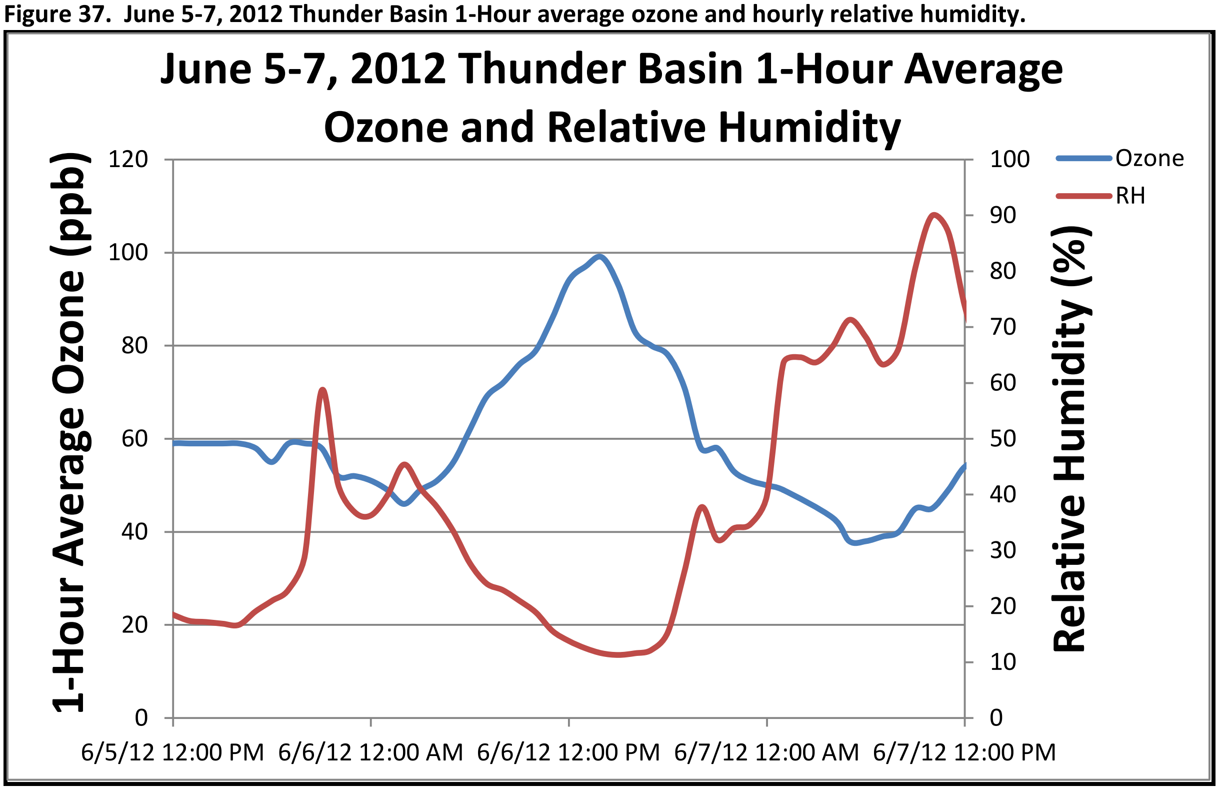


Figure 38. June 5-7, 2012 South Pass 1-Hour average ozone and hourly relative humidity.

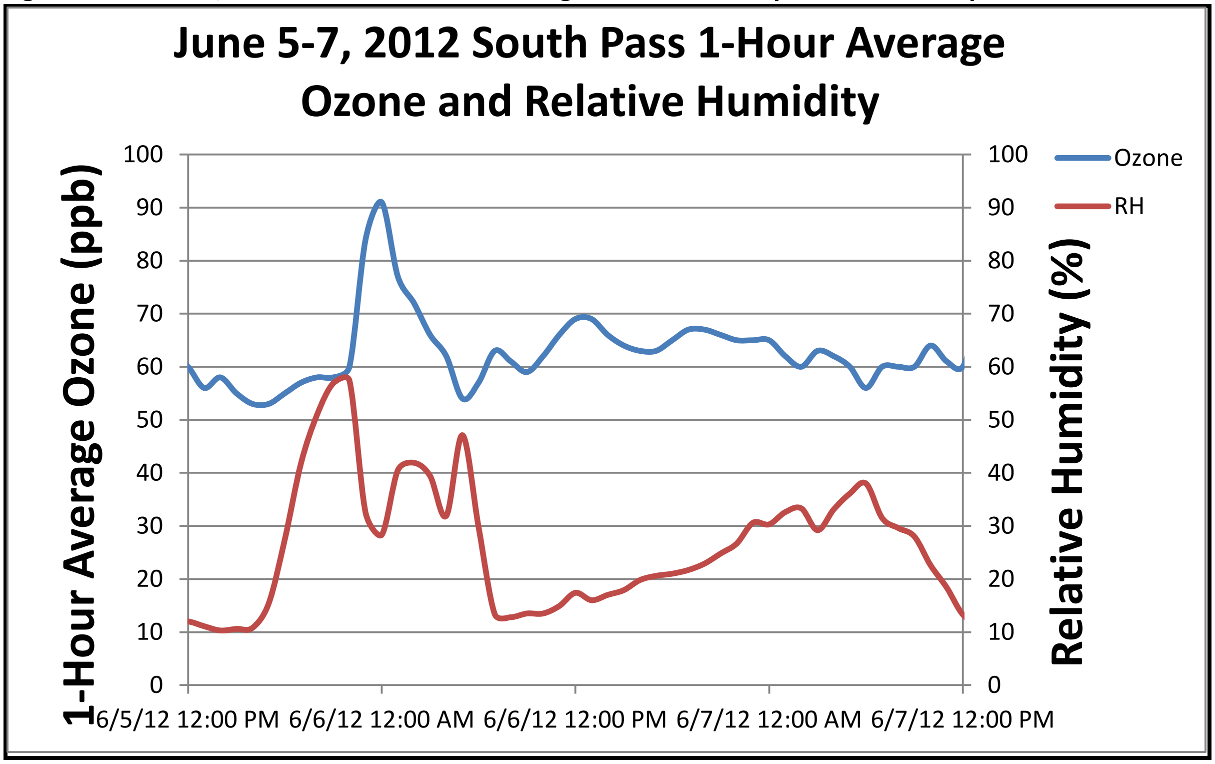
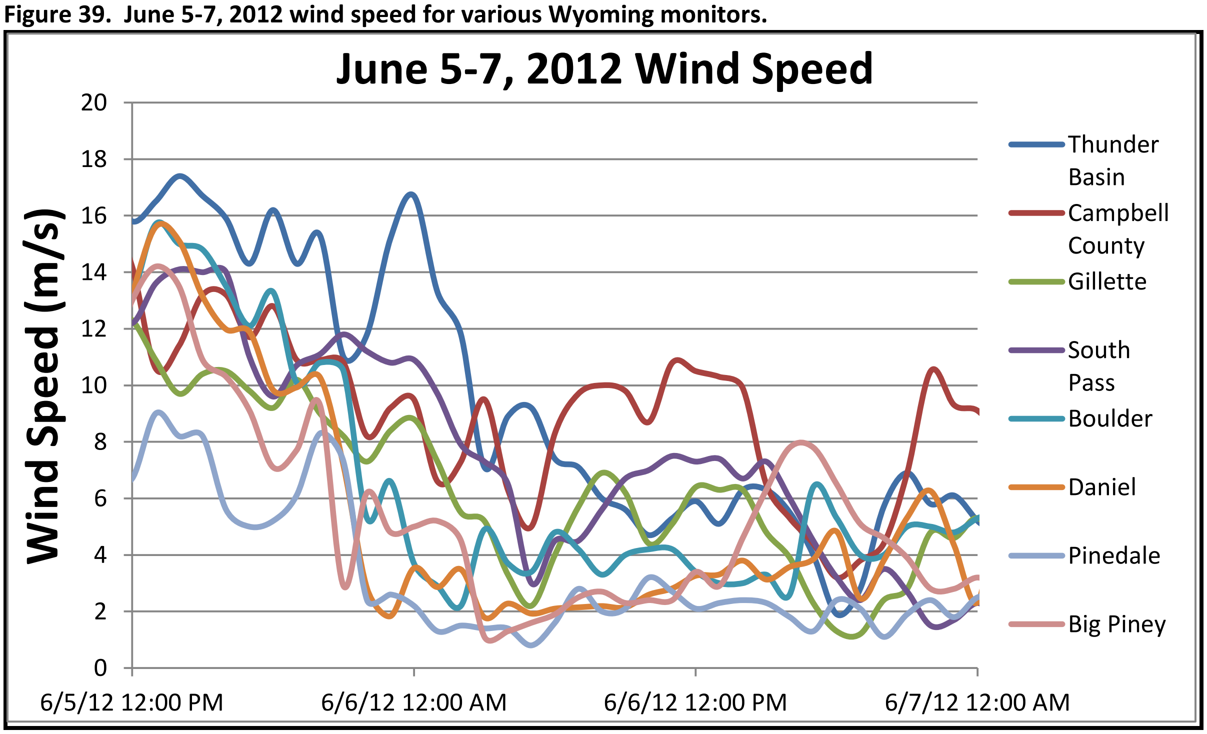
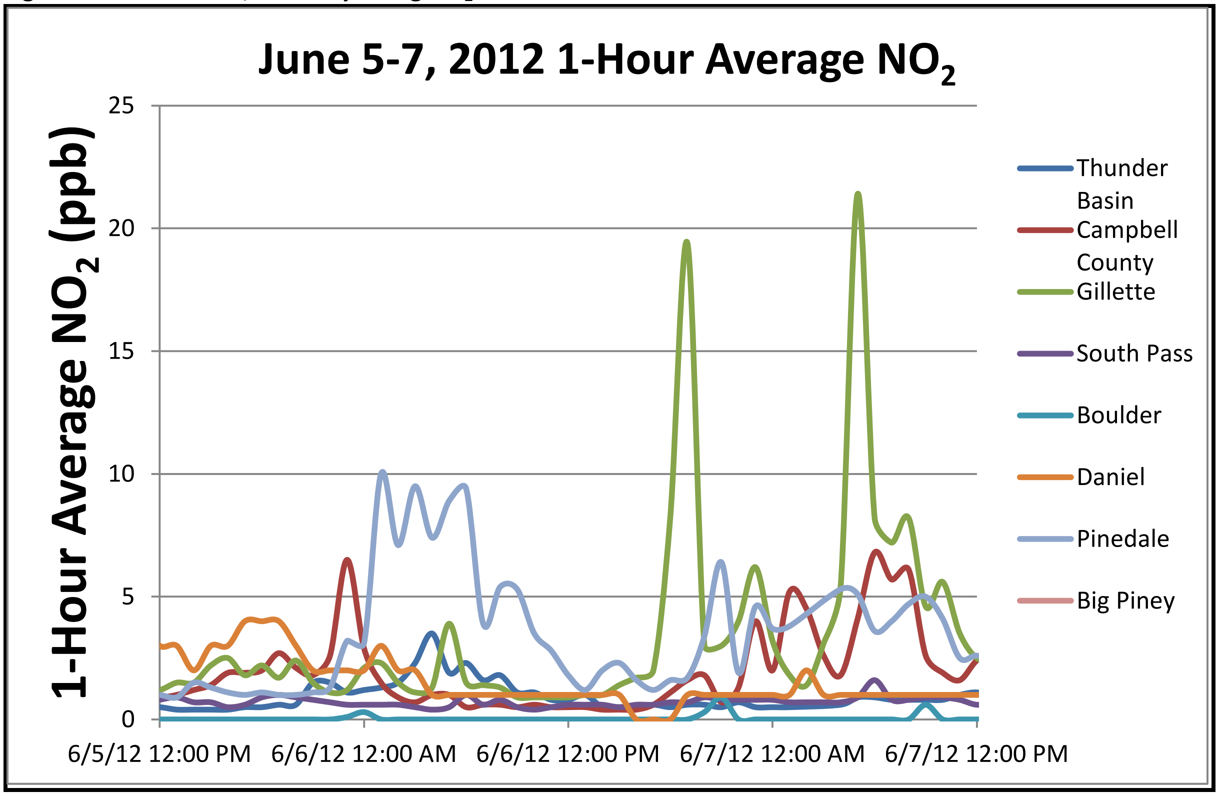


Figure 39. June 5-7, 2012 wind speed for various Wyoming monitors.



Lastly, NO_2 plays an important role in ozone formation. Without attempting to quantify NO_2 levels as they pertain to resultant ozone levels, a relative comparison of NO_2 levels can be made. Figure 40 depicts June 5-7, 2012 NO_2 for Thunder Basin, Campbell County, Gillette, South Pass, Boulder, Daniel, Pinedale, and Big Piney. With the exception of Gillette, 1-hour average NO_2 levels ranged between 0 and 2 ppb; near the detection level of the instrument.

Figure 40. June 13-15, 2012 Wyoming NO_2.



Figures 41-42 present the month of June 2012 and June 6-7, 2012 Gillette hourly NO_2, respectively. June 6-7, 2012 is representative of the diurnal cycle observed during the entire month of June. Furthermore, Figures 43-44 show the distribution (Box-and-whiskers plots) of 2011-2012 and June 2012 Gillette hourly NO_2 values from midnight to 11 pm MST, correspondingly. On both box-and-whiskers plots, NO_2 concentration increases during the early morning hours, decreases late in the morning, and increases during mid-evening. The June 6-7, 2012 hourly NO_2 displays a similar pattern compared to Figures 43 and 44.

Figure 41. June 2012 Gillette hourly NO_2.

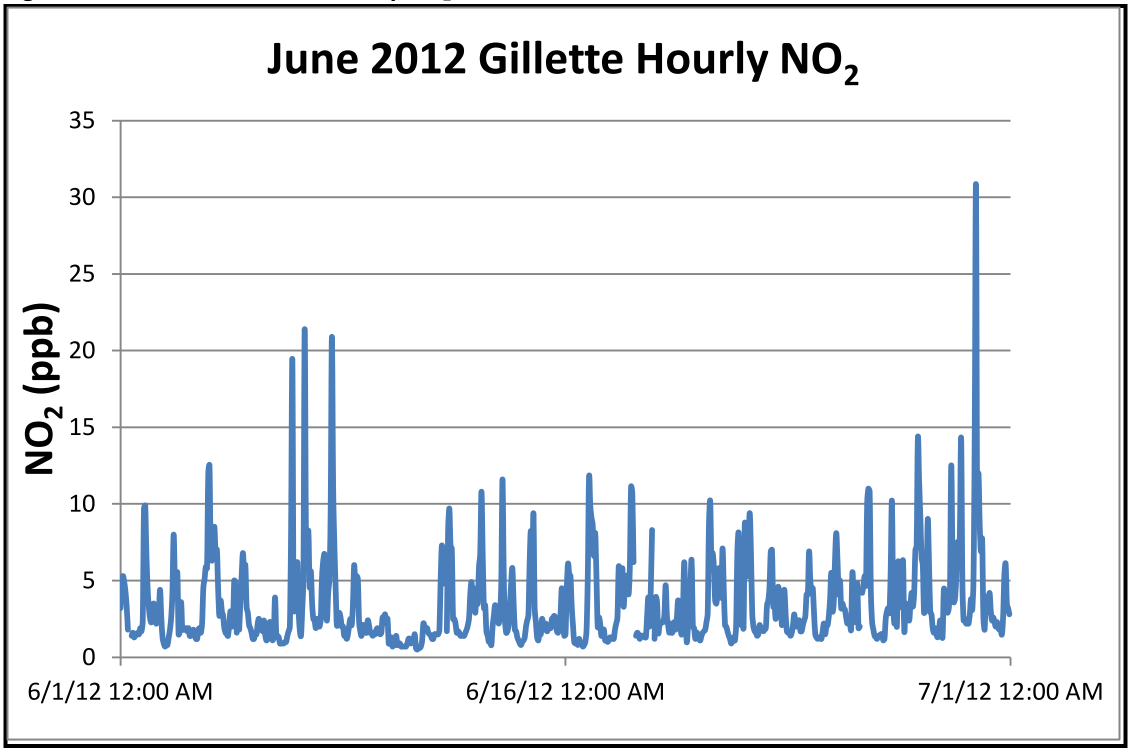


Figure 42. June 6-7, 2012 Gillette hourly NO_2.

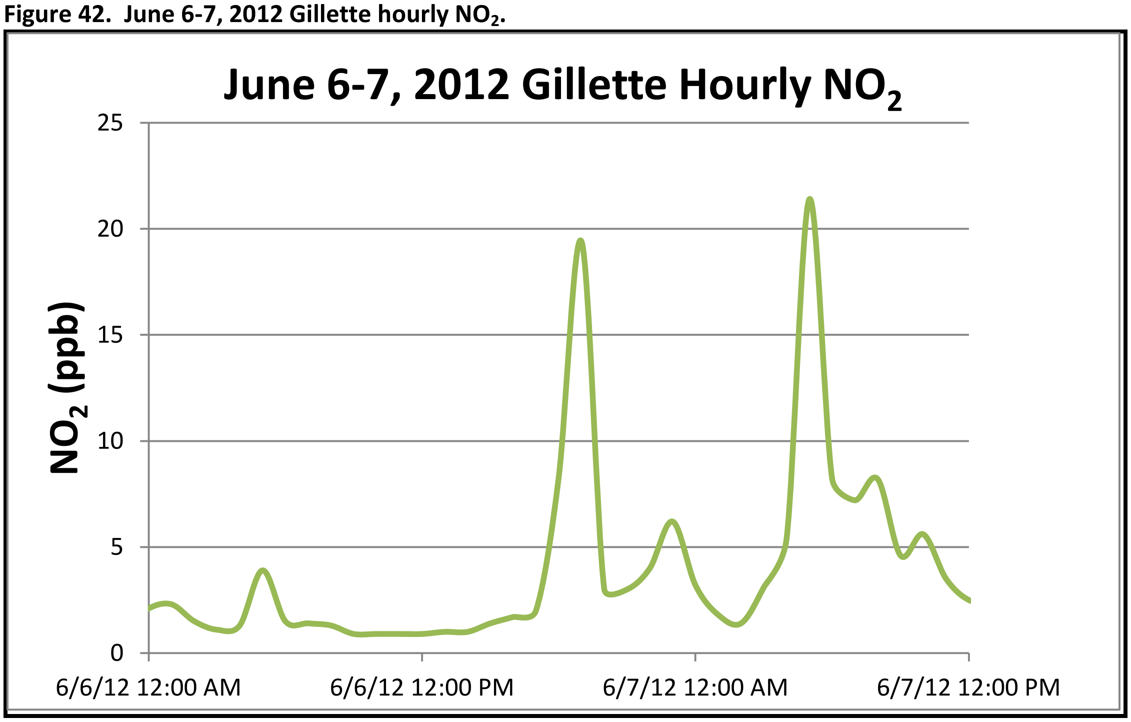


Figure 43. 20011-2012 Gillette box-and-whiskers plots of hourly NO_2 values from midnight to 11 pm MST. Click image to enlarge.

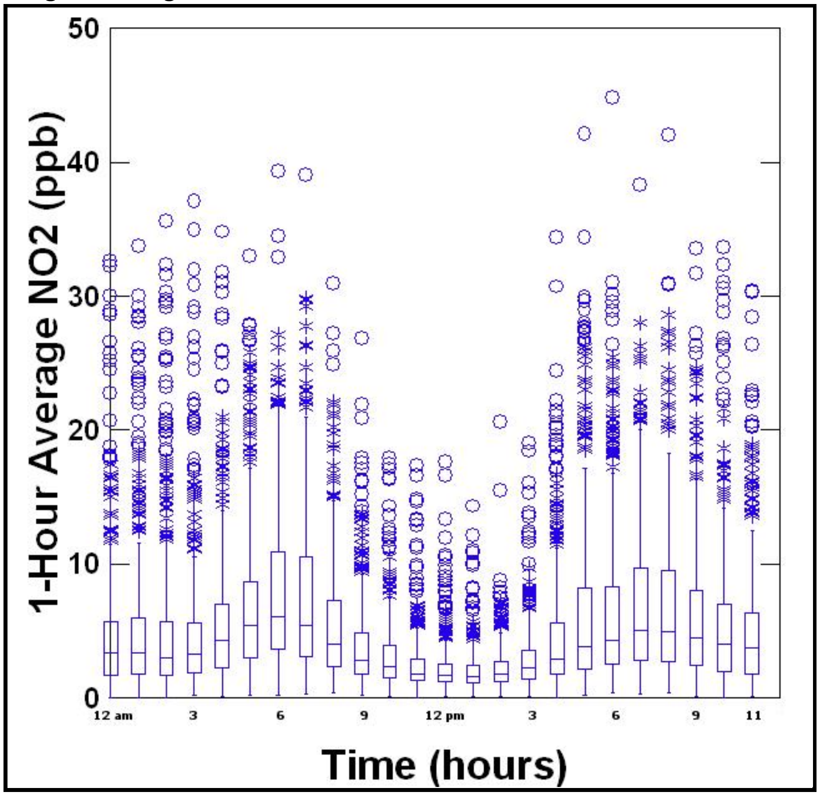
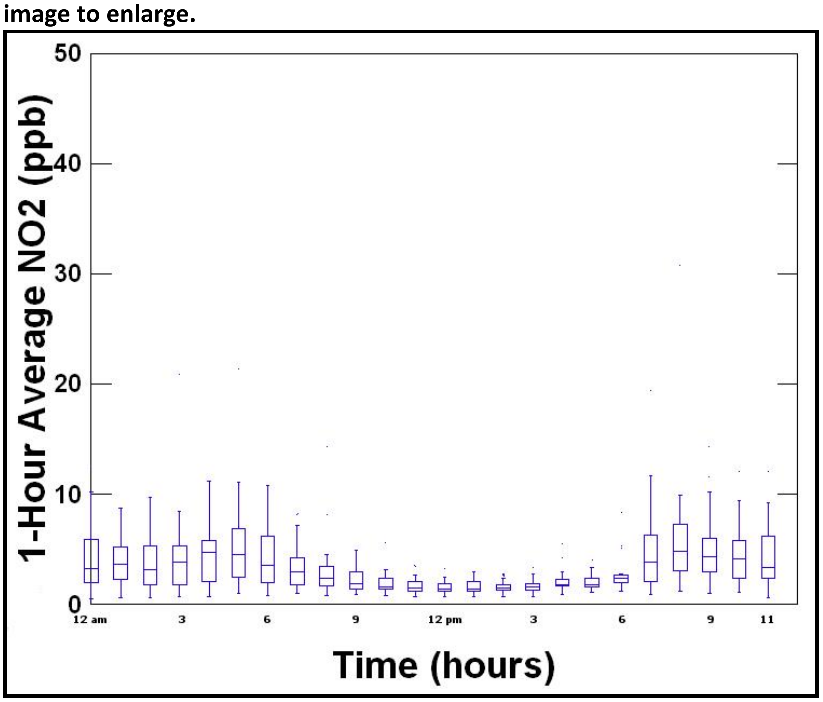


Figure 44. June 2012 Gillette box-and-whiskers plots of hourly NO_2 values from midnight to 11 pm MST. Click image to enlarge.



SUMMARY AND CONCLUSIONS

During the interval from late winter to late spring in the northern hemisphere, weather producing systems (i.e. tropospheric storm systems, upper level disturbances or upper level storm systems) aid in causing the tropopause to “fold” or descend into the troposphere where our weather occurs. Tropopause folding permits ozone-rich air from the stratosphere to enter the troposphere, also called an SI, creating the potential for ground level ozone monitors over the higher terrain of the western United States to experience elevated readings.

On June 6, 2012 an upper air level disturbance produced an SI affecting the Thunder Basin, Wyoming monitor resulting in a maximum daily 8-hour average ozone level of 88 ppb. Aiding in the elevated 8-hour levels were 1-hour average ozone values that were in the mid-to-upper 90’s ppb. Because of the SI, elevated ozone occurred at South Pass (91 ppb, 1-hour average) at 12 am MST, June 6, 2012 and continued at the other Wyoming sites during June 6, 2012.

It has been documented (T. S. ENVIRON 2008) that elevated ozone values can occur at the UGRB ozone monitors of Boulder, Big Piney, Pinedale, and Daniel because of light winds, snow cover, and strong inversions during the January-March winter ozone season. However, during the June 6, 2012 period of elevated ozone, strong winds (refer to Figure 39) buffeted the UGRB prior to the SI event, and no snow cover or strong inversions were present. Accumulation of surface-based ozone precursors did not occur because meteorological conditions were not supportive of precursor buildup prior to elevated ozone readings.

Statistical analyses performed on the Thunder Basin data show that the June 6, 2012 ozone data was statistically significantly higher than values recorded during June of each year starting with 2001 and ending in 2012. The AQD performed a careful evaluation of the June 6, 2012 episode, and is confident that the Thunder Basin event presented in this document is the result of a stratospheric intrusion.

The “Supporting Meteorological Data” sections of this document clearly show that an upper atmospheric disturbance and its attendant SI carried ozone-rich air from the stratosphere to the area around the Thunder Basin monitor during June 6, 2012. Due to the disturbance, tropospheric conditions were conducive for vertical mixing over the Thunder Basin area as evidenced by the “Vertical mixing as shown by lapse rates and boundary layer depth” section of this document. Furthermore, the “Research Flight Ozone Measurements Coupled With a Realtime Air Quality Modeling System” and “SI Origin Using Trajectories and Satellite Measurements” sections provide additional evidence of an SI, which began over the Gulf of Alaska, and subsequently moved toward Wyoming.

The SI meets the definition of a stratospheric intrusion as outlined in the preamble to “Treatment of Data Influenced by Exceptional Events” 40 CFR Parts 50 and 51 section IV(D)(5)(e). Specifically, air originated in the stratosphere and was transported directly to the earth’s surface via an upper level disturbance causing the Thunder Basin June 6, 2012 exceptional event. This event meets the specific criterion established in 40 CFR 50.14 (3)(iii) as described below.

Criteria **(A)** states that “[t]he event satisfies the criteria set forth in 40 CFR 50.1(j)”:

40 CFR 50.1 (j) requires that an exceptional event “affects air quality, is not reasonably controllable or preventable...” and is a “...natural event[s]”. The Exceptional Events Rule

Preamble and the 40 CFR 50 Appendices I & P specifically list stratospheric intrusion of ozone as a natural event that could affect ground level ozone concentrations. This packet includes data and graphics that display a weather disturbance and clearly shows an intrusion of stratospheric air that affected ambient air quality during June 6, 2012 at the Thunder Basin monitor.

Criteria **(B)** states that **"**[t]here is a clear causal relationship between the measurement under consideration and the event that is claimed to have affected the air quality in the area":

The causal relationship is a basic one in which the ozone standard exceedance was caused by tropospheric folding resulting in an SI. For the exceedance that occurred on June 6, 2012, an intrusion of stratospheric air occurred over or just to the upwind of the Thunder Basin monitor and injected ozone-rich air into the area above and surrounding the Thunder Basin monitor. The causal nature of the SI's impact on ozone values at the Thunder Basin monitor is further supported by the corroboration of ground-based air quality data to the spatial and temporal accuracy of the meteorological analysis.

Criteria **(C)** states that **"**[t]he event is associated with a measured concentration in excess of normal historical fluctuations, including background":

Statistical analysis of June 6, 2012 data clearly shows that the exceptional event was statistically significantly higher than data recorded during prior months of June from 2001 to 2012 at the Thunder Basin monitor.

Criteria **(D)** states that "[t]here would have been no exceedance or violation but for the event":

The SI allowed ozone-rich air to descend to the Thunder Basin monitor area and created elevated 1-hour average ozone values. The exceedances of the ozone National Ambient Air Quality Standards (NAAQS) would not have occurred "but for" the SI.

The 75th percentile hourly concentrations do not exceed 60 ppb on any of the years tested (2001-2012) for statistical significance. Hourly concentrations monitored during June 6, 2012 were outliers for the month of June 2001-2012. Statistics demonstrating that ozone levels were unusually elevated affirm that the exceedance of the ozone National Ambient Air Quality Standards (NAAQS) would not have happened "but for" the SI event having occurred during June 6, 2012.

In brief, the WDEQ/AQD concludes that an SI event occurred during June 6, 2012 resulting in an exceptional event. This exceptional event has passed the four criterion tests under 40 CFR 50.14 (3)(iii). Consequently, the WDEQ/AQD is requesting EPA's concurrence that the event was exceptional and for the exclusion from the Air Quality System (AQS) database of the Thunder Basin 1-hour average ozone data for the following times:

Table 5. Thunder Basin Times and Dates for AQS data exclusion.

Begin Time/Date(s)	End Time/Date(s)
0600 MST June 6, 2012	1900 MST June 6, 2012

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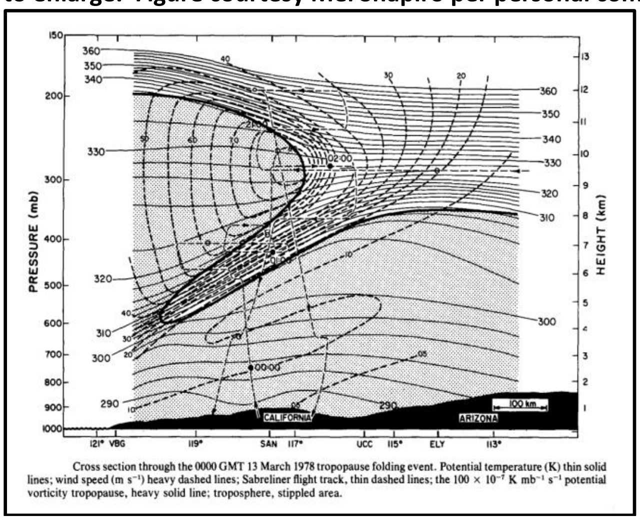
APPENDIX A - Documented Stratospheric Intrusion Events

March 12, 1978

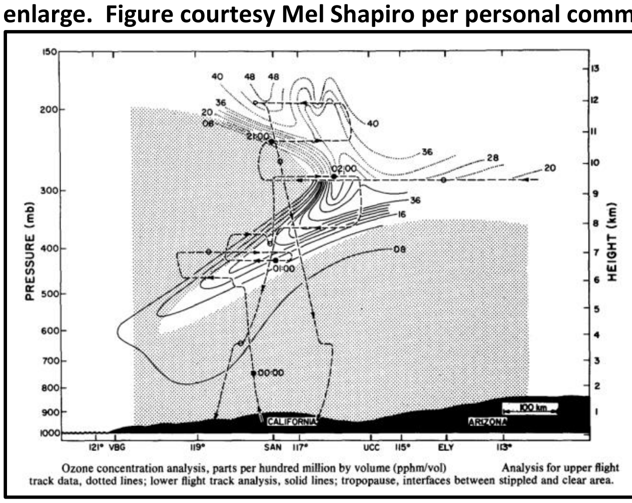
Much of the literature regarding SI's refers to Shapiro's May 1980 paper outlining the results of a research flight that flew through an SI on March 12, 1978 (Shapiro 1980). Equipped with a "fast-response ozone" analyzer, a research plane flew several transects through an SI over California. Shapiro produced vertical cross-sections of IPV, PT, and O_3 concentration from the flight data. Figures A and B portray cross-sections of IPV, PT, and the flight track and clearly show that the O_3 concentration increased when the plane flew through the SI.

Figure A. Cross-section through the 5 pm MST March 13, 1978 tropopause folding event. Potential temperature (K) thin solid lines; wind speed (meters per second) heavy dashed lines; flight track, thin dashed lines; the 100 x 10-7 K mb-1 s-1 potential vorticity Tropopause (1-PVU), heavy solid line; troposphere, stippled area. Click image to enlarge. Figure courtesy Mel Shapiro per personal communication.



Cross section through the 0000 GMT 13 March 1978 tropopause folding event. Potential temperature (K) thin solid lines; wind speed (m s^{-1}) heavy dashed lines; Sabreliner flight track, thin dashed lines; the 100 × 10^{-7} K mb^{-1} s^{-1} potential vorticity tropopause, heavy solid line; troposphere, stippled area.

Figure B. Cross-section through the 5 pm MST March 13, 1978 tropopause folding event. Ozone concentration analysis, parts per hundred million by volume (pphm/vol). Analysis for upper flight track data, dotted lines; lower flight track analysis, solid lines; tropopause, interfaces between stipple and clear area. Click image to enlarge. Figure courtesy Mel Shapiro per personal communication.



Ozone concentration analysis, parts per hundred million by volume (pphm/vol) Analysis for upper flight track data, dotted lines; lower flight track analysis, solid lines; tropopause, interfaces between stippled and clear area.

November 7-8, 1999

During 1999, the Mesoscale Alpine Programme captured an SI event over northern Italy from evidence obtained by using remote optical sensing technology known as the Raman Light Detection And Ranging (LIDAR) sensor (Aulerio, et al. 2005). The Raman LIDAR measures water vapor concentration, and combined with back trajectory analyses, an SI was detected which descended to 4 km AMSL and was ~500 meters thick in 1999 over northern Italy. In other words, the SI lowered to within 16,000 feet of the earth's surface and extended over the length of five football fields upward.

April 28, 2008

During 2008, the Stratosphere-Troposphere Analyses of Regional Transport (START08) field project utilized a research aircraft to measure a multitude of ambient air quality and meteorological parameters (L. L. Pan 2010). On April 28, 2008, Research Flight 4 penetrated the upper portion of an SI, which occurred over northern Missouri (refer to Figure C). Data from the flight reveals more direct evidence that O_3 concentrations increased as the plane entered the SI. Figure D shows the height of the flight path, and a cross-section with corresponding flight times, IPV, and PT as the plane entered the SI. As the plane penetrated the SI, the O_3 concentration increased to over 400 ppb, CO decreased, PT increased, and the RH decreased providing further evidence of an SI as evidenced by Figures E and F.

Figure C. Thin red line in plan-view is the flight path. Click image to enlarge.

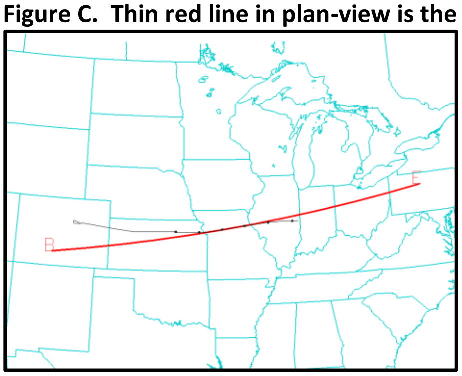


Figure D. Cross-section of flight path and IPV. Times are in MDT. Click image to enlarge.

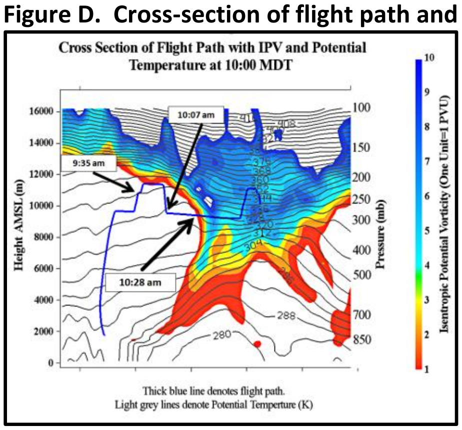


Figure E. Time series of ozone, carbon monoxide, and relative humidity during flight. Times are in MDT. Click image to enlarge.

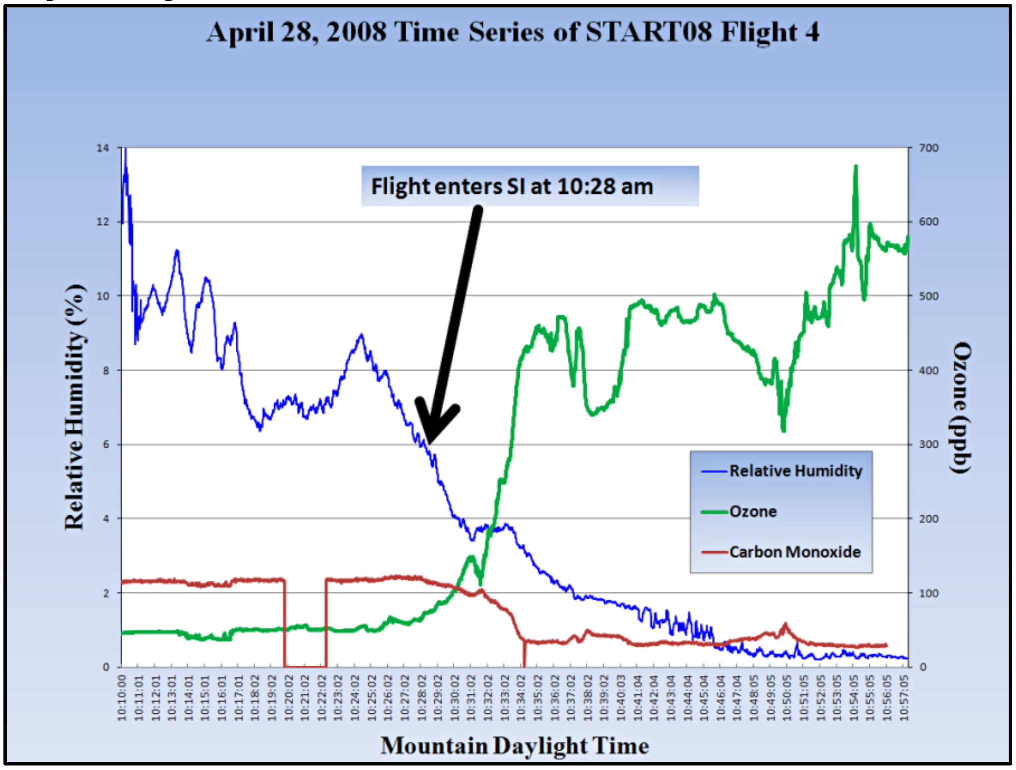
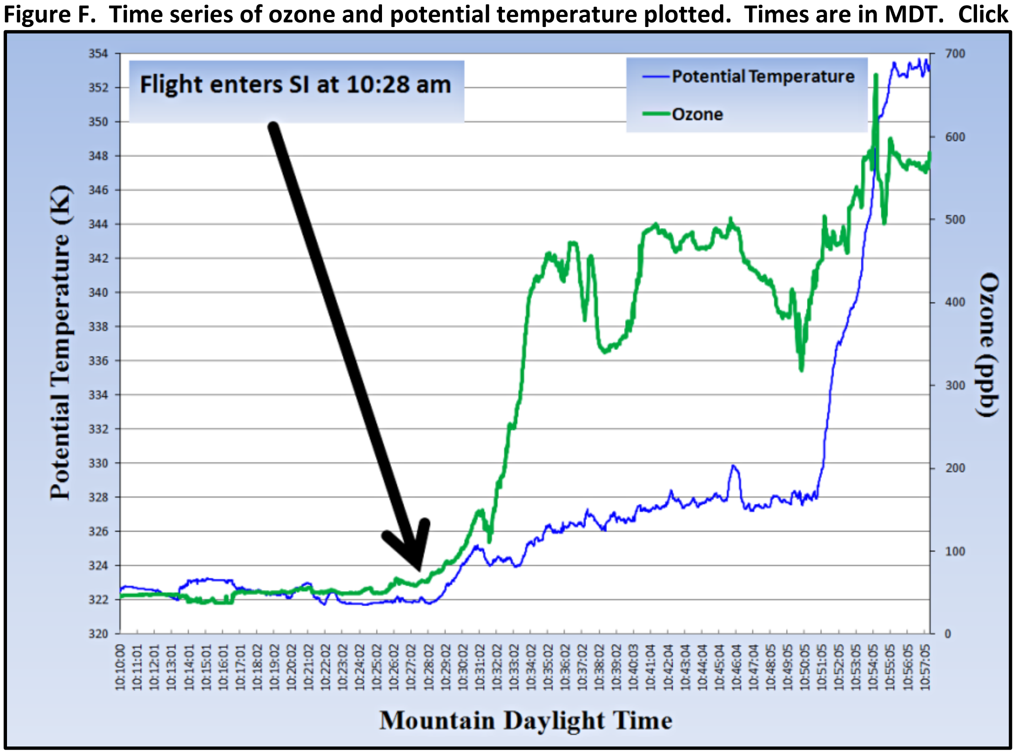


Figure F. Time series of ozone and potential temperature plotted. Times are in MDT. Click image to enlarge.

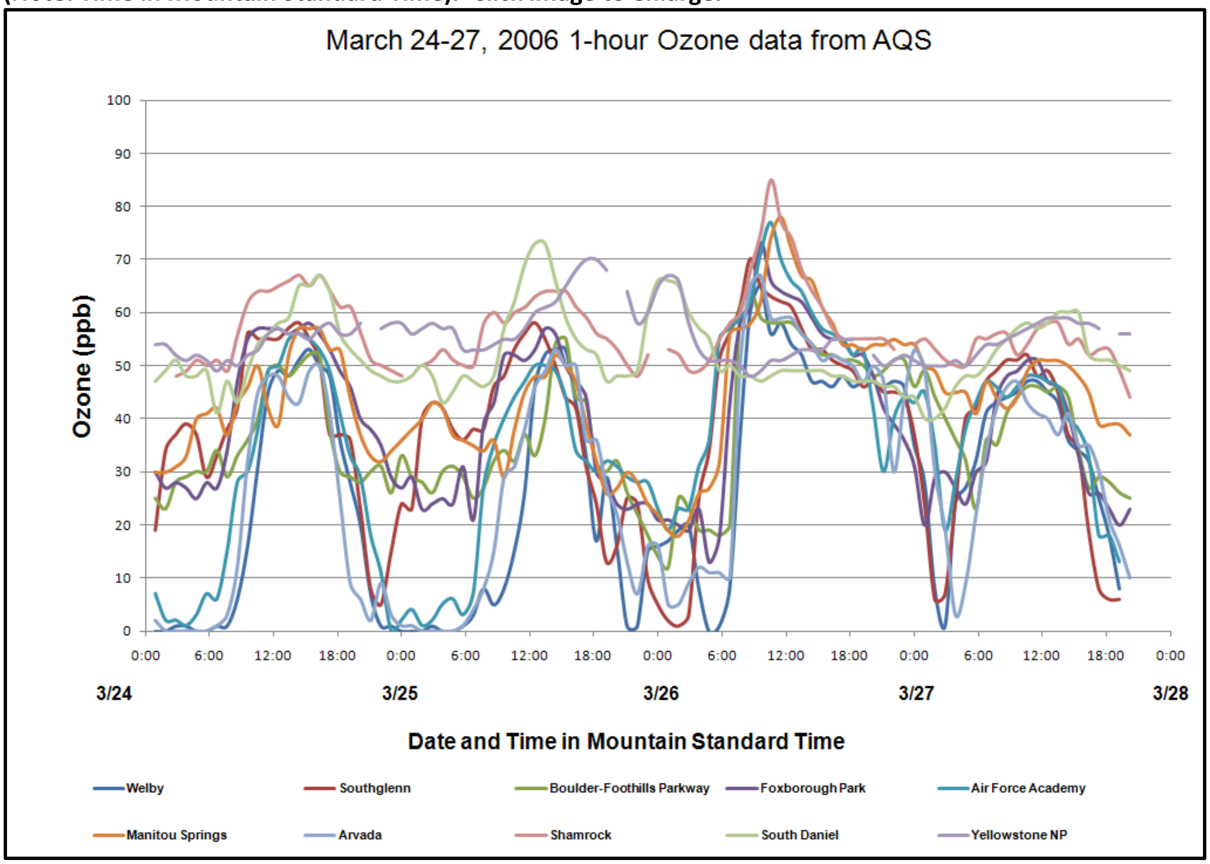


APPENDIX B - Diagnosis Example

Event: March 26, 2006 SI moving over Colorado ground based ozone monitors.

Between March 25, 2006 and March 27, 2006, a strong upper level system moved over Colorado and Wyoming. Air closest to the ground was well mixed due to winds associated with the movement of the weather system across the region. A well-mixed environment enhances the likelihood that stratospheric air can "mix-down" to the surface. In this instance, an SI associated with the passing weather disturbance injected ozone-rich air into the area resulting in abnormally high hourly ozone readings. Figure A shows several Colorado ozone monitors "spiking" well into the 70's and lower 80's ppb during the morning of March 26, 2006 for 1-hour average ozone.

Figure A. Various Colorado and Wyoming 1-hour average Ozone concentrations (ppb) from March 24-27, 2006 (Note: Time in Mountain Standard Time). Click image to enlarge.

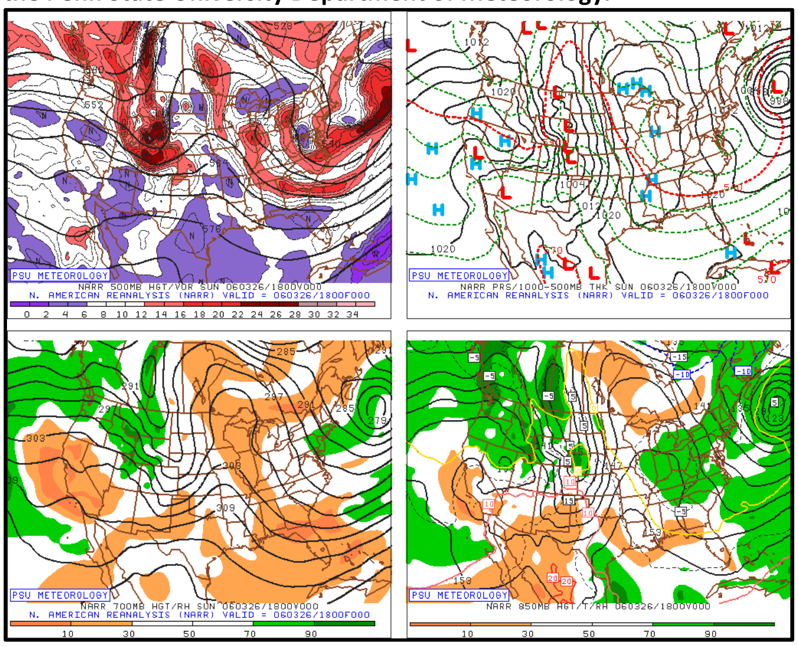


Supporting Meteorological Data: Weather Overview

The NARR for March 25-27, 2006 shows that an upper level weather system moved over Colorado. Figure B is a 4-panel graphic of 500 mb heights and vorticity, 700 mb heights and relative humidity, 850 mb heights/temperatures/relative humidity, and the surface pressure pattern at 11 am MST on March 26, 2007 (Please refer to Appendix C for a further explanation on how to interpret the NARR charts). Note the 500 mb circulation center over Colorado and Wyoming. Recall that upper level weather systems aid in tropopause folding, or the descent of ozone-rich air into the troposphere. Time stamps on the NARR charts are in Universal

Coordinate Time (UTC). To convert to Mountain Standard Time, subtract 7 hours from UTC (e.g. 18 UTC equates to 11 am MST).

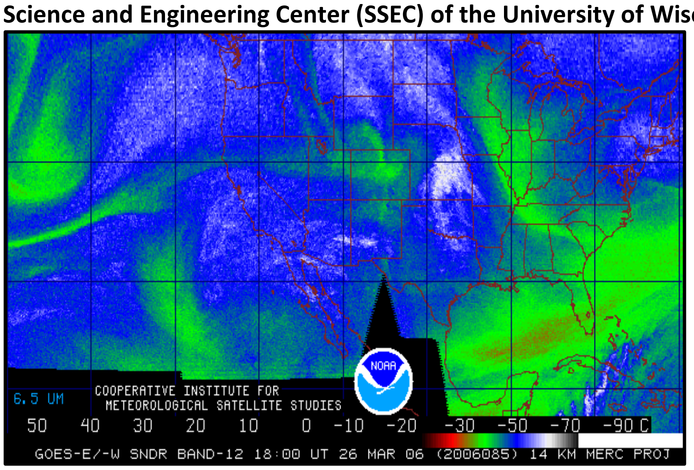
Figure B. North America Reanalysis valid at 11 am MST, March 26, 2006. Click image to enlarge. Click here for a time animation from 11 am March 25, 2007 to 11 am March 27, 2006. Graphic courtesy Fred Gadomski and the Penn State University Department of Meteorology.



Supporting Meteorological Data: GOES Band-12 Data[17]

In Figure C, GOES Band-12 data shows an upper level weather disturbance located over Colorado and Wyoming at 11 am MST on March 26, 2006. Note the dry air, depicted by the light green color in the 400 to 300 mb layer over southern Wyoming and northern Colorado. The same time convention of UTC applies for the GOES Band-12 images as in the case for the NARR graphics.

Figure C. 11 am MST, March 26, 2006 GOES Band-12 image. Click image to enlarge. Click here for a time animation from 5 pm March 25, 2006 to 4 pm March 26, 2006. Image courtesy of the Data Center at the Space Science and Engineering Center (SSEC) of the University of Wisconsin-Madison.



[17] GOES total column ozone data was unavailable during this SI event.

Supporting Meteorological Data: Upper Air RAOB's

RAOB's taken at the Denver airport on March 26, 2006 at 5am and 5pm, portray the lowering of the tropopause associated with the passing upper air disturbance and attendant dry air intrusion. Figures D and E show that the tropopause was approximately at the 200 mb level at 5 am (1200Z), and lowered to 450 mb at 5 pm (0000Z)[18]. To understand this comparison, note in Figure D the red line veering steeply to the right toward the top of the graphic. This represents the tropopause at 200 mb because air above the tropopause will start to warm with height. Figure E depicts the lowering of the tropopause to 450 mb. Note that the warming of air occurs closer to the bottom of the graphic representing a "lowering of the tropopause". One can determine the lack of moisture in the air by the increasing distance between the red contour and dashed black contour when comparing both graphics.

Figure D. Denver, Colorado upper air sounding at 5 am MST, March 26, 2006. Click image to enlarge. Image courtesy Plymouth State University Department of Atmospheric Science & Chemistry.

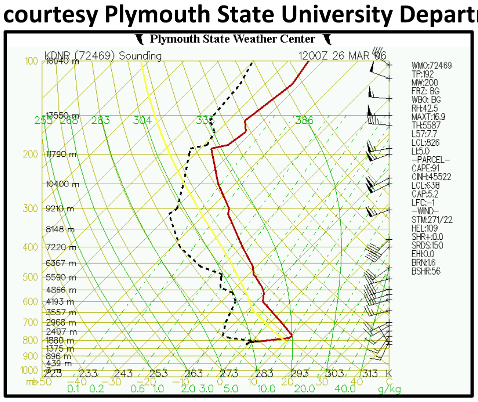
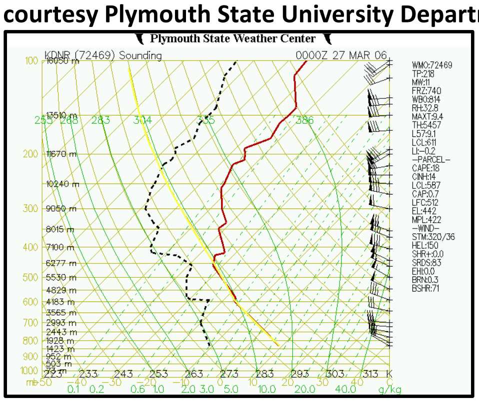


Figure E. Denver, Colorado upper air sounding at 5 pm MST, March 26, 2006. Click image to enlarge. Image courtesy Plymouth State University Department of Atmospheric Science & Chemistry.

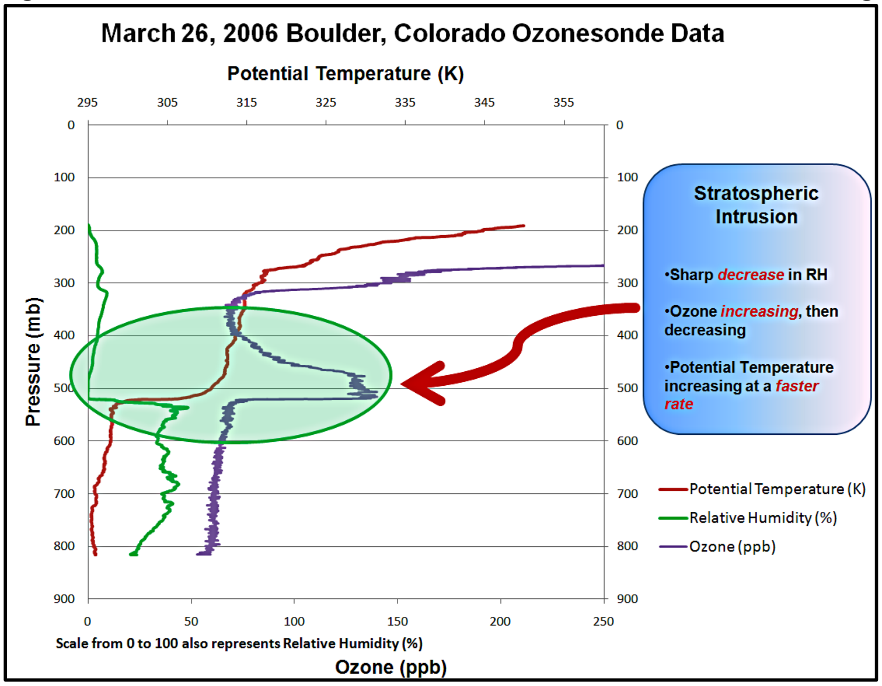


Additional evidence of an SI having occurred on March 26, 2006 comes from the Global Monitoring Division (GMD) of the Earth System Research Laboratory of the National Oceanic and Atmospheric Administration. The GMD released weekly ozonesondes that provide ozone, relative humidity, and potential temperature data from an instrument package attached to a balloon. An ozonesonde is like a RAOB but geared specifically toward capturing ozone concentrations. The GMD launched an ozonesonde on March 26, 2006 at 12:56 pm MST from Boulder, Colorado while an SI passed overhead. Figure F depicts the instrument flight data in

[18] Atmospheric pressure increases with altitude. When one descends in the atmosphere, pressure values increase.

the vertical. The SI is identified by its signature: a layer of dry air, higher ozone concentrations, and a potential temperature contour that steepens sharply indicating a fast rate of increase.

Figure F. Boulder, Colorado ozonesonde data from March 26, 2006. Click image to enlarge.



Supporting Meteorological Data: Isentropic Potential Vorticity, Relative Humidity, and Potential Temperature Cross-Sections

Using the 20-km RUC 0-hour analysis in time series, one can view the lifecycle of an SI. Figure G shows a map view where the cross-section was taken for use in this analysis.

Figure G. Map view of analysis cross-section. Click image to enlarge.

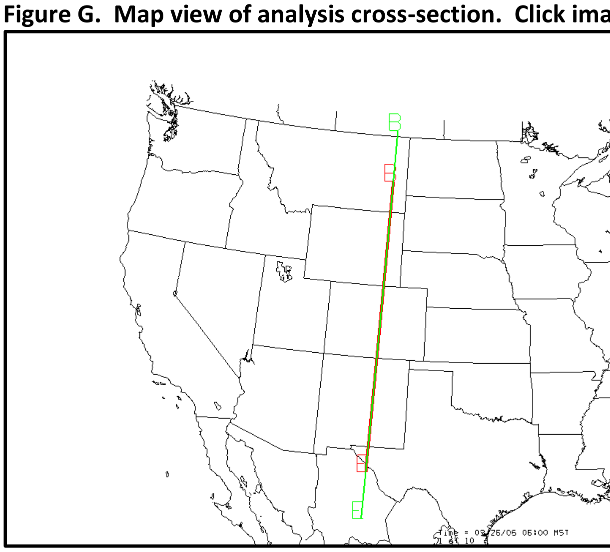


Figure H depicts IPV and PT along with a map view of the 500 mb heights and vorticity at 11 am March 26, 2006. The Denver-Colorado Springs I-25 corridor is approximately in the middle of the cross-section. The animated loop illustrates the 1-unit IPV surface descending along with the steeply sloping potential temperature surfaces, a clear SI signature. The right side of Figure H reveals that the passage of the 500mb storm system vorticity core over the Denver-Colorado Springs I-25 corridor corresponds to the 1-unit IPV surface having reached its lowest altitude.

Figure H. 11 am March 26, 2006 cross-section of IPV and potential temperature (left panel). 500 mb heights (black)/vorticity (blue-red) (right panel). Click image to enlarge. Click here for a time animation from 6 am to 3 pm, March 26, 2006.

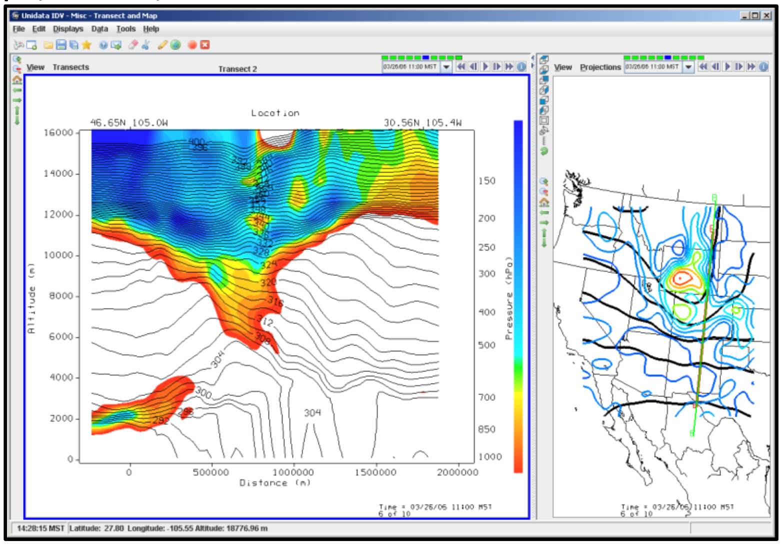
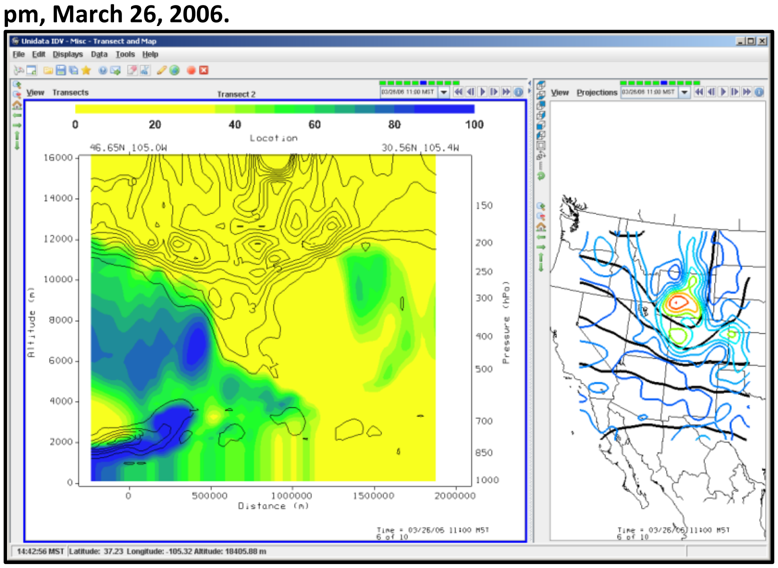


Figure I depicts IPV and RH along the same Denver-Colorado Springs I-25 corridor as in Figure 16. In the area where 1-unit of IPV descended to its lowest altitude, the air entrained was significantly drier than the air surrounding the intrusion. The combination of descending IPV and low RH air is another aspect supporting the presence of an ozone-rich stratospheric intrusion.

Figure I. 11 am MST March 26, 2006 cross-section of IPV and relative humidity (left panel). 500 mb heights (black)/vorticity (blue-red) (right panel). Click image to enlarge. Click here for a time animation from 6 am to 3 pm, March 26, 2006.



APPENDIX C – Boulder, Campbell County, Gillette, Daniel, and Pinedale June 5-7, 2012 1-Hour Average Ozone and Relative Humidity

Figure A. June 5-7, 2012 Boulder 1-Hour average ozone and hourly relative humidity.

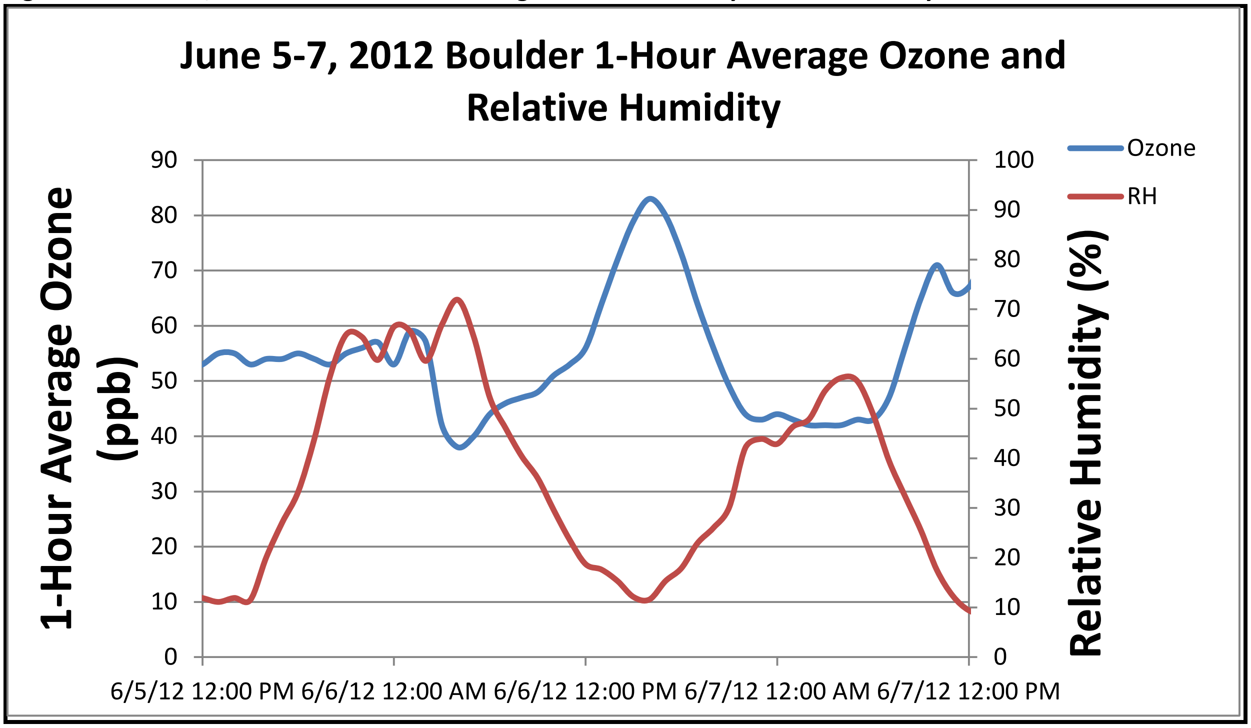


Figure B. June 5-7, 2012 Campbell County, 1-Hour average ozone and hourly relative humidity.

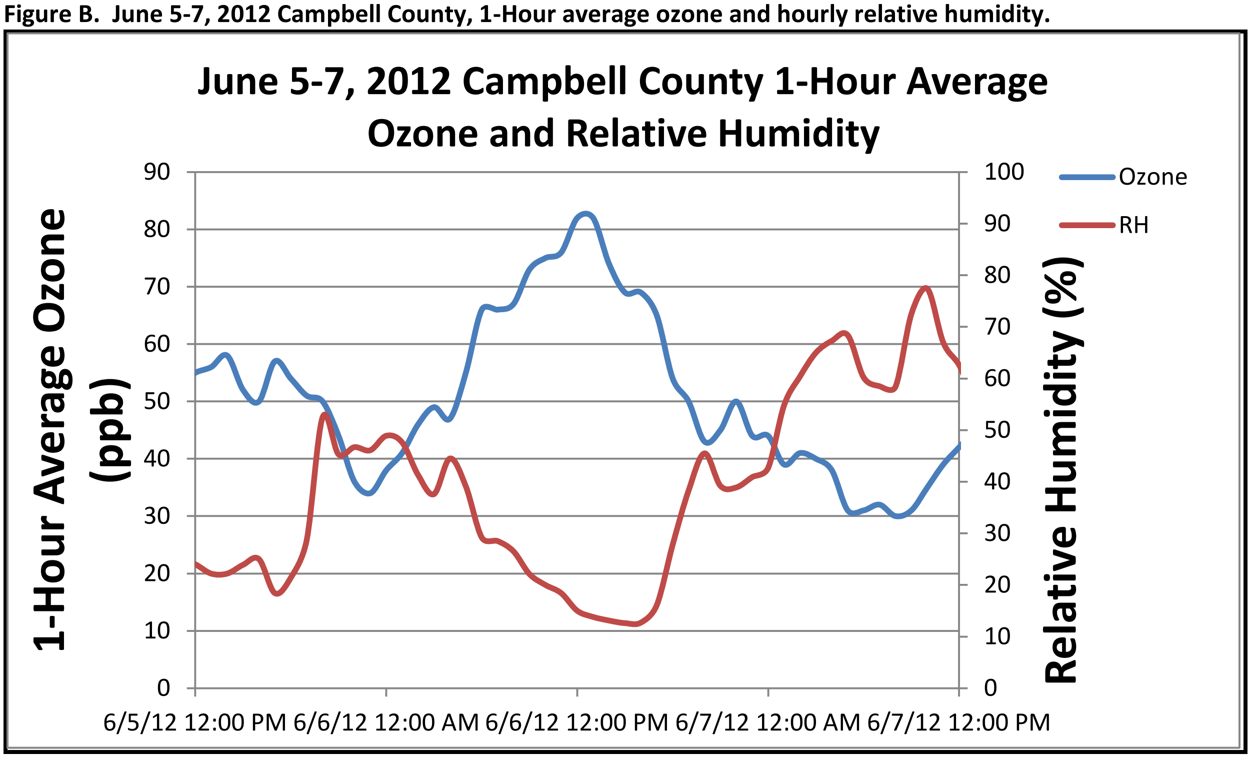


Figure C. June 5-7, 2012 Gillette 1-Hour average ozone and hourly relative humidity.

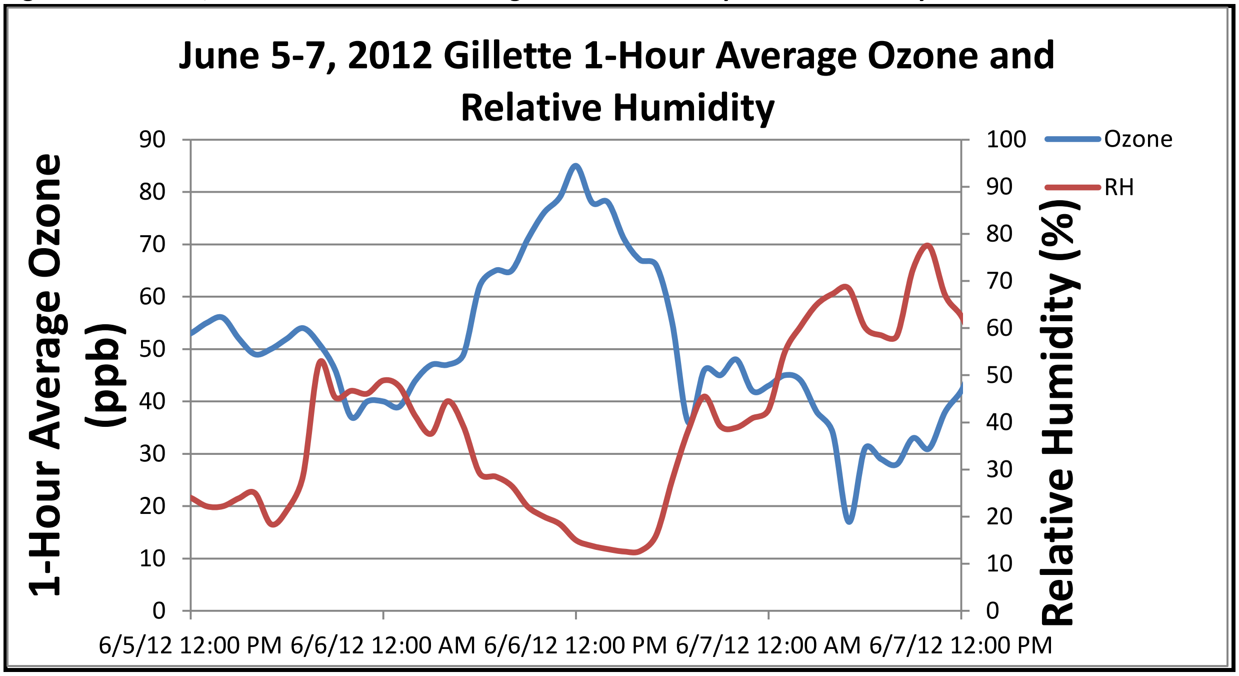


Figure D. June 5-7, 2012 Daniel 1-Hour average ozone and hourly relative humidity.

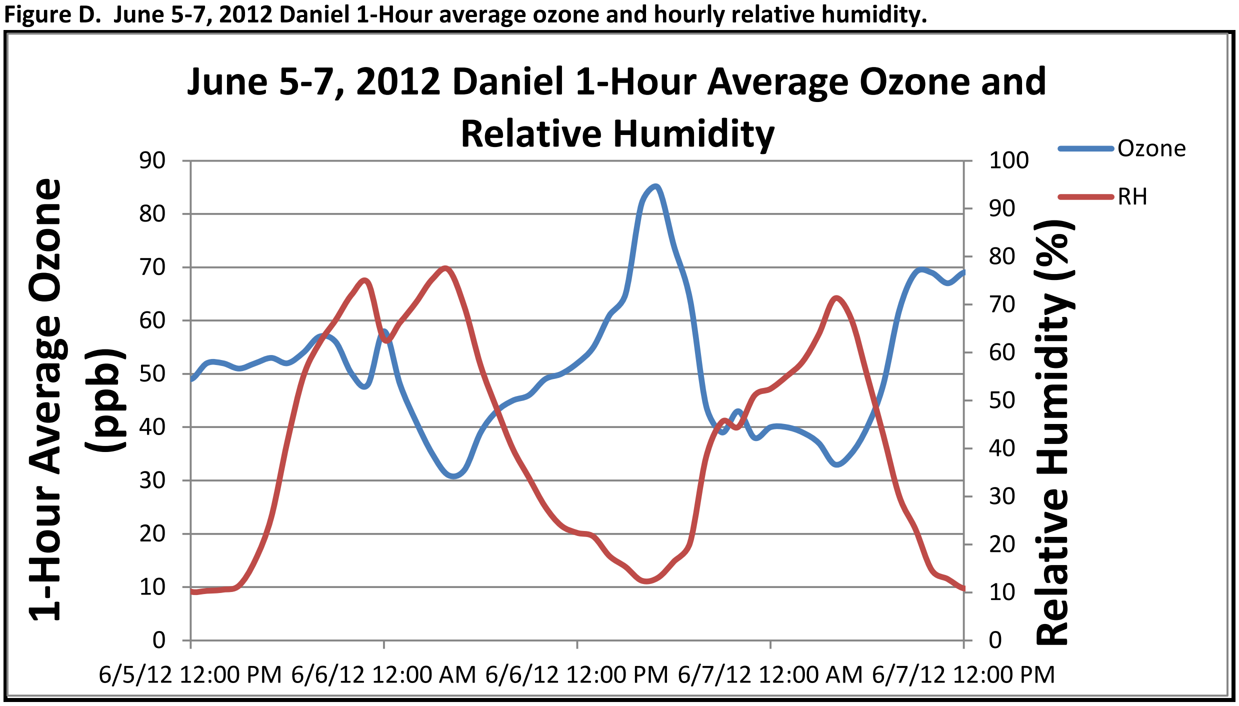
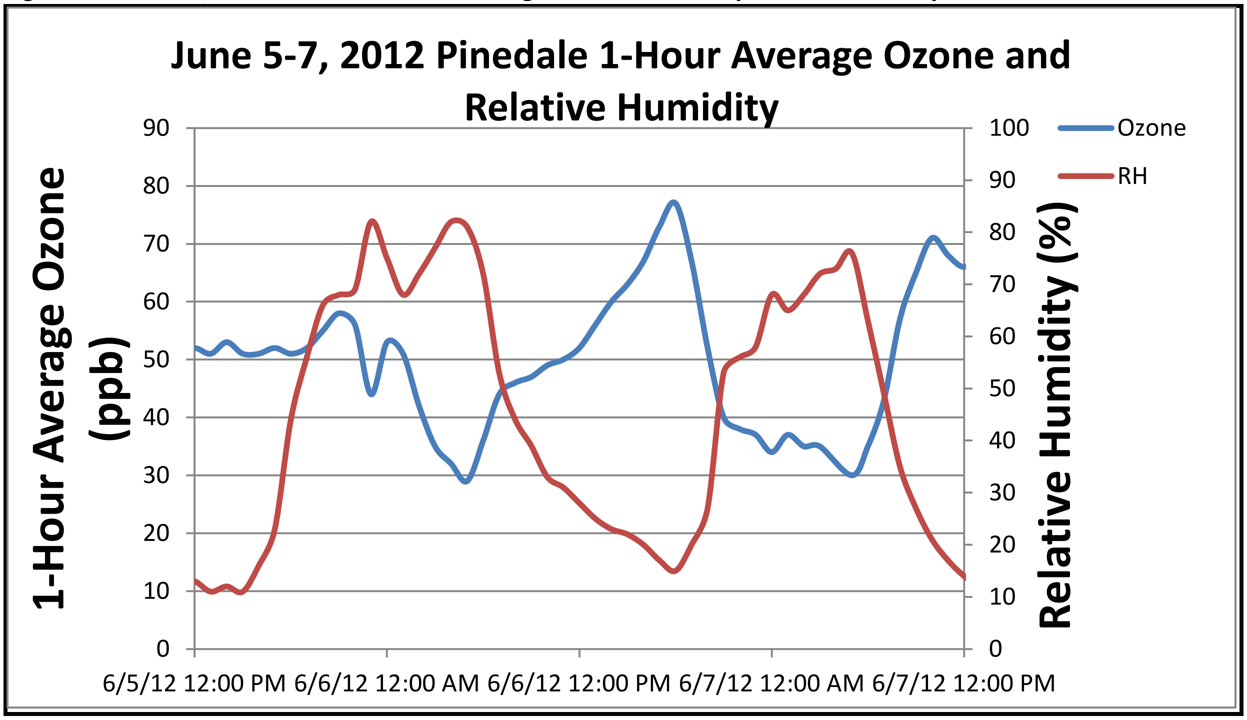
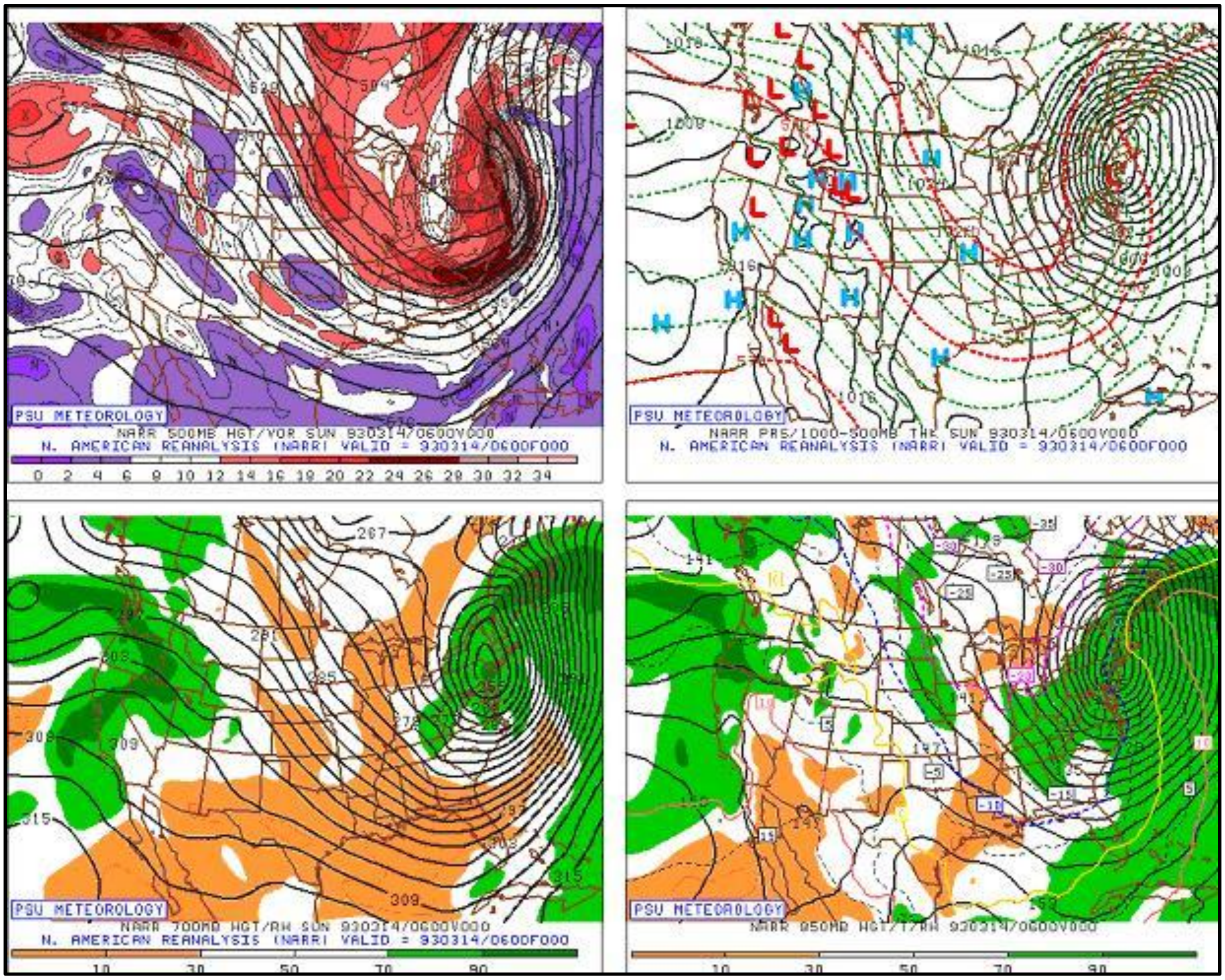


Figure E. June 5-7, 2012 Pinedale 1-Hour average ozone and hourly relative humidity.



APPENDIX D - NARR Explained

Example of the 4-panel NARR plot of 500 mb heights and vorticity, 700 mb heights and relative humidity, surface pressure and 1000-500 mb thickness, and 850 mb heights, temperature, and relative humidity. Explanation on how to interpret this chart follows. Graphic and NARR description courtesy Fred Gadomski and the Penn State University Department of Meteorology.



NARR 500mb Heights and Vorticity Panel – Top Left

The 500mb Heights and Vorticity Panel can be used to describe the steering flows of the atmosphere. These steering flows are located about 20,000 feet up (about halfway through the atmosphere) and generally direct major weather systems across the country. The black contours are isohypse (lines of constant height), and are contoured every 6 dm (the values on the isohypse are in decameters, i.e. 570 would actually be 5700m). The height of the 500mb level is how far you would have to go up in the atmosphere before the pressure drops to 500mb. Lower heights are usually found to the north while higher heights are usually found off to the south.

The red and purple shading on the map indicate areas of vorticity in the atmosphere. Vorticity is a measure of rotation throughout the atmosphere. Vorticity can either strengthen or weaken storm systems. Areas of red shading on the panel indicate positive vorticity, while areas of purple shading indicate negative vorticity. The darker the shading is, the stronger the vorticity. Areas of positive vorticity can strengthen areas of low pressure, and are sometimes referred to as “upper-level disturbances” or “upper-level energy”. The numbers on the map near areas of vorticity indicate the magnitude of the vorticity.

NARR 700mb Heights and Relative Humidity Panel – Bottom Left

The 700mb Heights and Relative Humidity Panel is an important panel used by meteorologists. The black contours are isohypse at the 700mb level (roughly 10,000ft), and are contoured every 3dm (the isohypse are in decameters, so 300dm is actually 3000m). The height of the 700mb level is how far you would have to go up in the atmosphere before the pressure drops to 700mb. The green and brown shading indicates the amount of relative humidity in the atmosphere at 700mb. (NOTE: This is NOT the relative humidity found at the surface). The green shading represents areas with a 700mb RH greater than 70% as indicated by the legend below the panel. Darker green shaded regions represent areas that have a 700mb RH greater than 90%. Light brown areas are regions where 700mb RH is less than 30%, with dark brown areas less than 10%. White areas on the map indicated regions where the RH is between 30% and 70%.

NARR Surface Pressure and 1000-500mb Thickness Panel – Top Right

The Surface Pressure and 1000-500mb Thickness Panel is useful when predicting where storm systems are moving and the type of precipitation that may fall from them. The black lines on this panel are isobars, (lines of constant pressure), and are contoured every four millibars (mb). Some of the isobars are labeled with numbers that usually range from 960mb (a strong low-pressure system), to 1050mb (a strong high pressure system). Low pressure systems are denoted by a red “L” while high pressure systems are denoted by a blue “H”.

The red and green dashed contours on the map are 1000-500mb thickness contours. The 1000-500mb thickness is the average depth of a column of air from 1000mb (surface level) to 500mb. The thickness can also be inferred to be the average temperature of a column of air from 1000mb to 500mb. The red dashed thickness contours are primary thickness contours (contoured every 30dm, the value on the thickness contours is in decameters), while the green dashed contours are secondary thickness contours (contoured every 6dm). The three primary thickness contours on the panel above are 510dm, 540dm, and 570dm. Thickness values lower than 510dm usually represent a dry, arctic air mass found in Canada or along the northern portion of the United States during winter, while thickness values higher than 570dm usually represent a warm and moist tropical air mass from the south. Thickness values can also be very useful in forecasting the different precipitation types from winter storm systems. More information on this can be found here.

850mb Temperature, and Relative Humidity

The 850mb Temperature and Relative Humidity panel is used by forecasters to get a general sense of what is going on in the lower-levels of the atmosphere just above ground level. The 850mb level is about 1500m above ground level, and is a valuable level to use when forecasting different the precipitation types associated with major winter storms.

The 850mb relative humidity (like the 700mb relative humidity), is scaled from 0% to 100%, with low humidity values shaded in a dark brown, and high humidity values shaded in a dark green. The difference between the relative humidity at 700mb and the relative humidity at 850mb is that the 850mb RH samples the lower-levels of the atmosphere and can be used to determine if low clouds such as stratus will form. It can also be used to give an estimate of the low level moisture in the atmosphere if you know the temperature of the air.

The other contours on the map are isotherms. The yellow contour on the map labeled with a 0 is the 850mb 0°C isotherm. Isotherms in intervals of 5°C are shown as well, with the -10°C isotherm shown as a blue dashed line, the -20°C shown as a pink dashed line, the 10°C isotherm shown as a solid orange line, and the 20°C isotherm shown as a solid red line.

APPENDIX E - AQS Data – AMP 350, Raw Data Report for Thunder Basin, Campbell County, Gillette, Big Piney, Boulder, South Pass, Daniel, and Pinedale 1-hour average ozone for June 5-7, 2012 (Click image to read report).

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

User ID: RBN

RAW DATA REPORT

Report Request ID: 1097335

Report Code: AMP350

May. 13, 2013

GEOGRAPHIC SELECTIONS

Tribal Code	State	County	Site	Parameter	POC	City	AQCR	UAR	CBSA	CSA	EPA Region	Method	Duration	Begin Date	End Date
	56	005	0123												
	56	005	0456												
	56	005	0800												
	56	013	0099												
	56	035	0099												
	56	035	0100												
	56	035	0101												
	56	035	0700												

PROTOCOL SELECTIONS

Parameter Classification	Parameter	Method	Duration
CRITERIA	44201		

SELECTED OPTIONS

Option Type	Option Value
RAW DATA EVENTS	INCLUDE EVENTS
DAILY STATISTICS	MAXIMUM
UNITS	STANDARD
MERGE PDF FILES	YES
INCLUDE NULLS	YES

SORT ORDER

Order	Column
1	STATE_CODE
2	COUNTY_CODE
3	SITE_ID
4	PARAMETER_CODE
5	POC

GLOBAL DATES

Start Date	End Date
2012 06 05	2012 06 07

APPLICABLE STANDARDS

Standard Description
Ozone 1-hour Daily 2005

Selection Criteria Page 1

APPENDIX F - AQS Data – AMP 350NW, Raw NAAQS Ozone Average Data Report for Thunder Basin, Campbell County, Gillette, Big Piney, Boulder, South Pass, Daniel, and Pinedale 1-hour average ozone for June 5-7, 2012 (Click image to read report).

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

User ID: RBN

RAW DATA NAAQS AVERAGES

Report Request ID: 1097339 Report Code: AMP350NW May. 13, 2013

GEOGRAPHIC SELECTIONS

Tribal Code	State	County	Site	Parameter	POC	City	AQCR	UAR	CBSA	CSA	EPA Region	Method	Duration	Begin Date	End Date
	56	005	0123												
	56	005	0456												
	56	005	0800												
	56	013	0099												
	56	035	0099												
	56	035	0100												
	56	035	0101												
	56	035	0700												

PROTOCOL SELECTIONS

Parameter Classification	Parameter	Method	Duration
CRITERIA	44201		

SELECTED OPTIONS

Option Type	Option Value
SINGLE EVENT PROCESSING	INCLUDE EVENTS
DAILY STATISTICS	MAXIMUM
MERGE PDF FILES	YES

SORT ORDER

Order	Column
1	STATE_CODE
2	COUNTY_CODE
3	SITE_ID
4	PARAMETER_CODE
5	POC

GLOBAL DATES

Start Date	End Date
2012 06 05	2012 06 07

APPLICABLE STANDARDS

Standard Description
Ozone 8-Hour 2008

Selection Criteria Page 1

APPENDIX G - AQS Data – AMP 350NW, Raw Data Report Thunder Basin, Campbell County, Gillette, Big Piney, Boulder, South Pass, Daniel, and Pinedale all air quality and meteorological parameters for June 5-7, 2012 (Click image to read report).

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

User ID: RBN

RAW DATA REPORT

Report Request ID: 1097337 Report Code: AMP350 May. 13, 2013

GEOGRAPHIC SELECTIONS

Tribal Code	State	County	Site	Parameter	POC	City	AQCR	UAR	CBSA	CSA	EPA Region	Method	Duration	Begin Date	End Date
	56	005	0123												
	56	005	0456												
	56	005	0800												
	56	013	0099												
	56	035	0099												
	56	035	0100												
	56	035	0101												
	56	035	0700												

PROTOCOL SELECTIONS

Parameter Classification	Parameter	Method	Duration
ALL			

SELECTED OPTIONS

Option Type	Option Value
RAW DATA EVENTS	INCLUDE EVENTS
DAILY STATISTICS	MAXIMUM
UNITS	STANDARD
MERGE PDF FILES	YES
INCLUDE NULLS	YES

SORT ORDER

Order	Column
1	STATE_CODE
2	COUNTY_CODE
3	SITE_ID
4	PARAMETER_CODE
5	POC

GLOBAL DATES

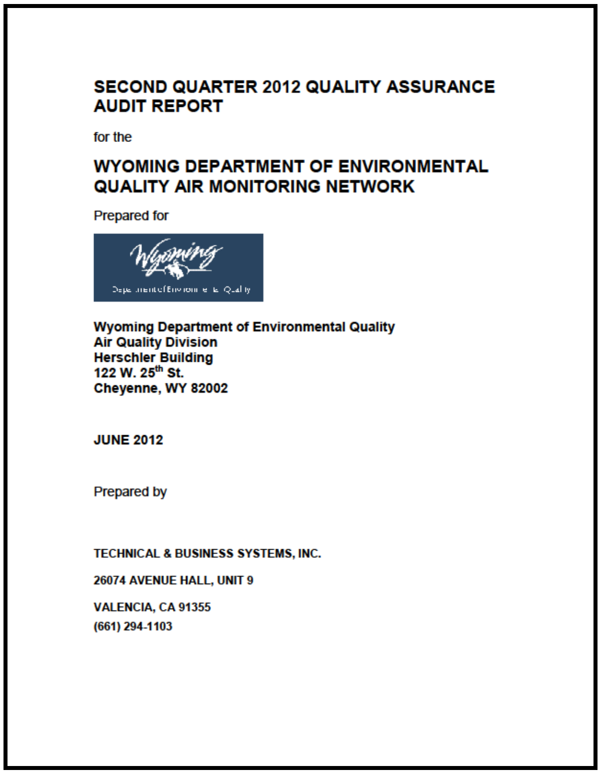
Start Date	End Date
2012 06 05	2012 06 07

APPLICABLE STANDARDS

Standard Description
CO 1-hour 1971
Lead 3-Month 2009
Lead 3-Month PM10 Surrogate 2009
Lead Quarterly 1978
NO2 Annual 1971
Ozone 1-hour Daily 2005
PM10 24-hour 2006
PM25 24-hour 2006
SO2 1-hour 2010

Selection Criteria Page 1

APPENDIX H - Thunder Basin 2nd and 4th Quarter 2012 QA Audit Reports (Click images to read reports).



SECOND QUARTER 2012 QUALITY ASSURANCE AUDIT REPORT

for the

WYOMING DEPARTMENT OF ENVIRONMENTAL QUALITY AIR MONITORING NETWORK

Prepared for

Wyoming Department of Environmental Quality
Air Quality Division
Herschler Building
122 W. 25th St.
Cheyenne, WY 82002

JUNE 2012

Prepared by

TECHNICAL & BUSINESS SYSTEMS, INC.
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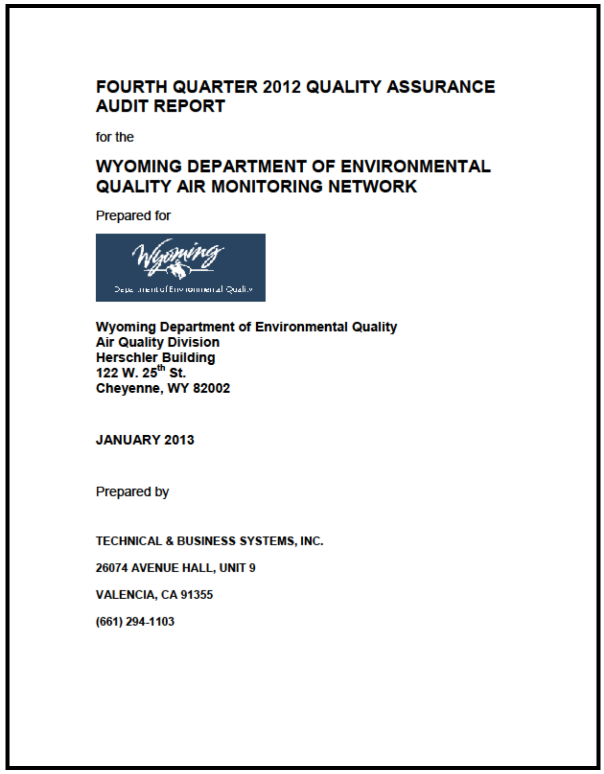
VALENCIA, CA 91355
(661) 294-1103



FOURTH QUARTER 2012 QUALITY ASSURANCE AUDIT REPORT

for the

WYOMING DEPARTMENT OF ENVIRONMENTAL QUALITY AIR MONITORING NETWORK

Prepared for

Wyoming Department of Environmental Quality
Air Quality Division
Herschler Building
122 W. 25th St.
Cheyenne, WY 82002

JANUARY 2013

Prepared by

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